



Review article

A comprehensive analysis of nanofluids and their practical applications for flat plate solar collectors: Fundamentals, thermophysical properties, stability, and difficulties

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ABSTRACT

The increasing energy demand and continuous confrontation of energy generation costs are preceded by a terrible depletion of fossil fuel power reserves and increased environmental pollution. In the recent years, renewable energy grew quickly to face the responsibility of the unforeseen energy problem. Flat plate solar collectors (FPSC) are well-known and widely used, thus utilised in low and medium thermal different domestic applications. However, FPSCs are less efficient due to their limited ability of solar energy to be converted into thermal energy due to the inefficient heat transfer in solar fluids on the collector's flow tubes. In recent decades, new technologies have enabled the manufacturing of particles in nanometre dimensions (usually less than 100 nm), suspended consistently and stable in traditional solar liquid or so-called nanofluid (NF) and have improved the effects of thermophysical features. The use of NFs as an innovative solar fluid can be reasonably considered as a powerful method of increasing the performance of the FPSC. This paper provides recent advances related to experimental and theoretical studies on NFs applications in the FPSC. Several parameters affecting the thermal efficiency of FPSC are extensively analysed, including the type of nanoparticles (NP)s, size/shape of the NPs, NPs concentration, mass flow rate and solar radiance. This paper also provides a comprehensive review and analysis of progress in the field of NFs, such as the applications of NFs, types, preparation, thermophysical properties, stability, chemical and physical methods for stability, mathematical formulas, and stability evaluation. Finally, the main challenges and future trends mentioned by the researchers while using NFs in solar thermal collectors such as the viscosity, instability, corrosion, operation cost, pumping power, pressure drop and behaviour of surfactant usage, which are assumed helpful to newcomers, are the focus areas of this research.

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1. Introduction

The world has been recently focusing on energy conservation due to the foundation of human development and worldwide politics and economy. To reduce the environmental effect of conventional energy sources, new energy sources should be developed. Therefore, Renewable energy technologies have higher efficiency and are more favourable. These technologies are generated by converting natural phenomena into energy types. They include wind, hydropower, wave, tidal, solar energy, biomass. Among them, solar energy is infinite and widely distributed in the vast majority of world and can significantly affect the world's economy, environment and politics (Mussard, 2017). The role of solar energy in today's energy production is significantly growing. The hourly solar radiation on the surface of the earth is higher than the annual energy consumption.

All forms of energy in the world comes from the sun. Besides, solar radiation can be harnessed in various natural and synthetic processes on the earth's surface. Fig. 1 shows that solar energy is transformed into various types of energy such as electrical, chemical, mechanical, and thermal. The solar collector is a heat exchanger specialised in the conversion of sunray into energy kinds such as electrical energy by photovoltaic cells (PV) in the photovoltaic application, thermal energy by solar thermal collectors in solar thermal applications and into both electrical and thermal by PV/T collectors. Solar collectors have two major categories of solar radiation receiving methods, namely, solar collectors concentrate and solar nonconcentrated collectors' flat plate solar collector (FPSC). FPSC has been extensively applied in many fields with thermal applications. Solar collectors absorb and convert solar radiation into heat energy for thermal application and move out the heat to a solar liquid passing across them.

Solar fluid is essential in a solar collector system for carrying heat Imran et al. (2016). The following criteria should be considered when selecting a heat transfer liquid for the solar system: thermal capacity, coefficient of expansion, viscosity, freezing point, boiling point, and flash point. In solar heating systems, traditional heat transfer fluids such as water and air are widely utilised. Water with high specific heat and low viscosity is nontoxic and inexpensive, thus one of the most widely popular operational fluids in solar water heating systems. Common traditional heat transfer fluids include water, air, hydrocarbon oils, glycol/water mixture and silicones. Different mechanical equipment and engineering processes such as heat exchange devices, chemical processes, power generation, cooling or heating applications and microelectronics are used. Given that these fluids have lower thermal conductivity, the fluids cannot transfer high amounts of heat in thermal applications.

FPSC is more suitable, easy to design, robust, and requires less maintenance. It is a critical application of solar energy for both domestic and industrial purposes since it absorbed solar energy and converted it to heat, transmitting heat to the household water in the tank by suitable work fluid (Al-Yasiri and Szabó, 2019). The low efficiency of the FPSC energy conversion is a significant drawback due to the coefficient of heat transfer between absorber and operation fluid being low.

One of the recent trends towards enhancing the FPSC performance is utilising nanomaterials in solar fluids (i.e., NFs) as working fluids instead of traditional fluids to achieve enhanced thermal efficiency. Eastman (2014) first proposed the concept of NFs as the mixture of a base fluid and nanoparticles (NPs) (<100 nm in size) as is a colloidal mixture. Thermophysical properties were advanced and effectively provided better thermal transfer and heat absorption than traditional fluids. Theoretical and experimental observations showed that NFs are extremely

Nomenclature

U_L	Overall heat transfer loss coefficient, $W/m^2 K$
U_t	Top loss coefficient, $W/m^2 K$
U_{ba}	Bottom loss coefficient, $W/m^2 K$
U_e	Edge Loss coefficient, $W/m^2 K$
P_{wr}	Pressure loss ratio
T_a	Ambient temperature, K
T_p	Plate temperature, K
G_t	Global solar radiation
N	Number of glazing
I	intensity of radiation, W/m^2
h_a	Heat transfer coefficient of air, $W/m^2 K$
A_b	Absorption area of collector, m^2
A_c	Total area of collector, m^2
A_e	Area of edge surface, m^2
C_p	Specific heat, $J/kg K$
F_R	Collector heat removal factor
I	Intensity of solar radiation, W/m^2
k	Thermal conductivity, $W/m K$
Q_u	Useful heat gain, W
R	Thermal resistance, K/W
Q	Heat flow, W
T	Temperature, K
C	Geometric concentration ratio
f	Modifier
x_b	Thickness of back insulation, m
W	Width between risers, m
D	Diameter of riser tube, m
k_b	Thermal conductivity of back insulation, $W/m K$
Nu	Nusselt number
F'	The collector efficiency factor
C_b	Bond conduction
W	Fin spacing, m
Ra	Rayleigh number
Pr	Prandtl number
FR	Heat removal factor

Subscripts and superscripts

f_o	Fluid outlet
n	Empirical shape factor
vol	Volume
b	Collector tilt angle
a	Ambient
d	Solar declination angle
bf	Base fluid
p	Solid particle
fi	Fluid inlet

Greek symbol

τ	Transmittance of a glass cover
ε_p	Emittance of plate
ε_g	Emittance of glass
δ	Solar declination angle
α	Absorptance of the absorber plate

ϕ	Nano particle volume fraction
θ	Incidence angle
η_o	Optical efficiency
ρ	Density, kg/m^3
η	Thermal efficiency of collector
σ	Stefan Boltzmann constant, $W/m^2 K^4$
μ	Dynamic viscosity

Abbreviations

SEM	Scanning electron microscope
TEM	Transmission electron microscope
DLS	Dynamic light scattering
UV	Ultraviolet
CFD	Computational Fluid Dynamics
SWCNT	Single Wall Carbon Nanotube
DI	Water deionised water
GNP	Graphene nanoplatelets
Al_2O_3	Alumina
SiO_2	Silica
CNT	Carbon nanotube
FPSC	Flat plate solar collector
NFs	Nanofluids
NPs	Nanoparticles
PVT	Thermal photovoltaic collector
SWHS	Solar water heating system
SDBS	Sodium dodecyl benzene sulfonate
MWCNT	Multi-Walled carbon nanotubes
PV	Photovoltaic panel
DW	Distilled water
EG	Ethylene Glycol

promising and can be replaced with conventional fluids to enhance solar collectors' performance. NFs are powerful tools for the solar system, thus resolving energy-related issues. Nanomaterials are recently produced by nanometric and are critical to nanoscience and nanotechnology research. Nanotechnology science is expanding the research and development among several countries worldwide (Li et al., 2009).

Many studies were conducted to examine and discuss the NFs technologies used to develop solar flat plate collectors. Among them, Sint et al. (2017) studied energy efficiency and NP concentration for FPSC using the NF of copper–water. The theoretical analysis found that using 2% concentration of NP increases collector's efficiency by 5% in comparison to water. Kiliç et al. (2018) carried out the efficiency enhancement of FPSC using nanofluid (TiO_2 /water at 2% concentration). The efficiency increased by 48.67% for 0.2 vol%, while 36.20% in used water as working fluid. Ziyadanogullari et al. (2018) experimental study was carried out in three different NF concentrations: Al_2O_3 , CuO and TiO_2 at 0.2%, 0.4% and 0.8%, respectively. The CuO–water mixture was identified as the clearest among all fluids. Genc et al. (2018) conducted a short numerical NF with water and alumina in FPSC at a flow rate of 0.06 kg/s and 0.04 kg/s and volume fractions of 1%, 2% and 3%. SWHS produced a maximum of 83.9% efficiency at 0.06 kg/s. The temperature outlet increased by 7.2% when the volume fraction was 3%. Akram et al. (2021) experimentally investigated the effect of f-GNPs, SiO_2 and ZnO nanofluids on the efficiency of FPSC. The weight fraction of the nanoparticle considered was 0.1% and the mass flow rate was 1.6 kg/min. The efficiency of the FPSC was found to be greater than water with

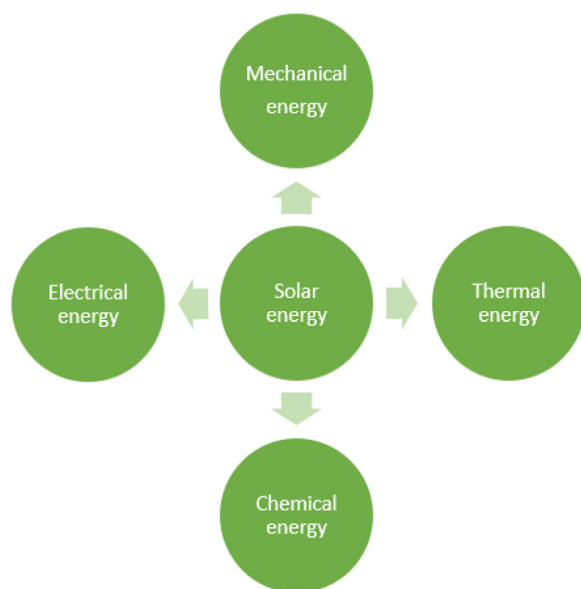


Fig. 1. Conversion of solar energy.

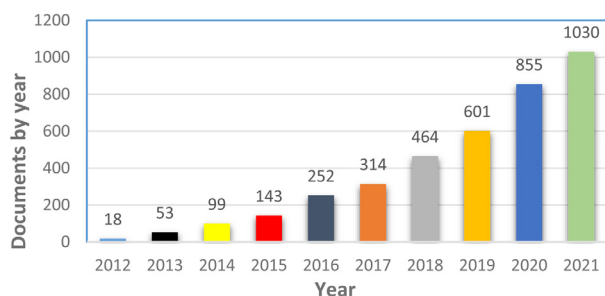


Fig. 2. Statistics of documents in Scopus database indicating the keywords “NFs in FPSC”.

using F-GNPs, ZnO and SiO₂ nanofluids by 17.45%, 13.05%, 12.36%, respectively.

Many works of literature on solar collectors improved via NFs have been reported (Al-Yasiri et al., 2021). Several countries have also carried out extensive research on the use of NFs in solar energy. Thousands of publications in the literature annually covering applications for NFs in various heat transfer fields exist. Fig. 2 shows the publication statistics of FPSCs efficiency for the last ten years, indicating the increased attention given to NFs as technology develops.

This paper presents a comprehensive review and analysis of the key facts in the field NFs with their application in FPSC. A detailed review of NF research is important since researchers need help for recent developments and identify the potential gap in NF research. Works reviewed included numerical, theoretical, and experimental investigations up to date on the usage of the common kinds of NF as solar fluid in FPSC. This review focuses on the improvement of the thermal performance of FPSC systems, while representing the main parameter for evaluating nanomaterial utilisation in FPSC systems. The impact of several parameters on the thermal efficiency of the FPSC including NP types, NPs size, NPs shape, NPs concentration, mass-flow rates, temperature, and acidity (pH), is examined in greater detail.

Moreover, difficulties in production processes, high production cost, and NF stability are obstacles to the commercialisation of NFs. Many major topics related to NFs are also covered in the sections of this current research, including an overview of FPSC,

Table 1

Solar energy collectors' concentration ratios and operating temperature Chamsa-ard et al. (2017) and Sajjadnejad et al. (2020).

Collector type	Concentration ratio	Temperature °C
Flat type collector (FPC)	$C \leq 1$	30–80
Evacuated type collector (ETC)	$C \leq 1$	50–150
Compound parabolic collector (CPC)	$1 \leq C \leq 5$	60–250
Parabolic trough collector (PTC)	$10 \leq C \leq 80$	400–500
Linear Fresnel collector (LFC)	$15 \leq C \leq 400$	100–450
Parabolic dish reflector collector (PDRC)	$100 \leq C \leq 1000$	100–600

Energy analysis of FPSC, synthesis of NFs, physical methods and chemical methods for enhanced stability of NFs, methods evaluation stability of NFs, and properties of NFs (viscosity, specific heat, pressure drops, density, thermal conductivity, convective heat transfer). Also, this work concludes by discussing on challenges of NFs.

2. Solar energy collectors

Solar energy collectors are thermal circulation devices that convert sunray into direct energy inside solar fluids. It is the main part of every solar system (Wang et al., 2015). The solar collectors are divided into two main categories, namely, nonconcentrated (stationary) and concentrated. In general, a nonconcentrated collector has the same solar radiation collection and interception area. In contrast, a concentrated collector for sun tracking usually has concave surfaces for reflecting and focusing sunbeam radiation on smaller area, with flux increasing. Concentrated collectors are appropriate for applications at high temperatures. A significant number of solar collectors exist on the market (Kumar et al., 2019). Fig. 3 shows the solar energy collectors, and the upper temperature limits and concentration ratios of these collectors are listed in Table 1.

3. Flat plate solar collector (FPSC)

The FPSC is a stationary collector and an exchanger system that transforms sunray to thermal energy in solar systems. When solar radiation penetrates the glazing and reaches the absorber plate, the energy is absorbed and transformed into the transferred heat to the fluid that passes through the absorber flow tubes to increase temperature. FPSCs may be classified as unglazed and flat glass plates (Hossain et al., 2011).

The advantages and disadvantages of FPSCs are summarised as follow:

- FPSC is inexpensive to manufacture.
- FPSC is permanently fixed in place, thus is no need to track the sun.
- Various kinds of FPSC have been built, ranging from glass plates to plastic plates. Many different materials, such as aluminium, copper, steel, iron, and various working fluids such as water, NF and air. Fig. 4 shows different types of FPSC.
- Solar collectors that use flat plates are easy to install and require little maintenance.
- However, in cold weather uses, these systems have significant disadvantages, which impact their technical feasibility and economy. With low insolation and ambient temperatures in northern Europe during the winter season, FPSCs have low thermal efficiency. Moreover, heat losses, heat transfer circulation loop and inadequate thermal insulation are the disadvantages of the FPSC.

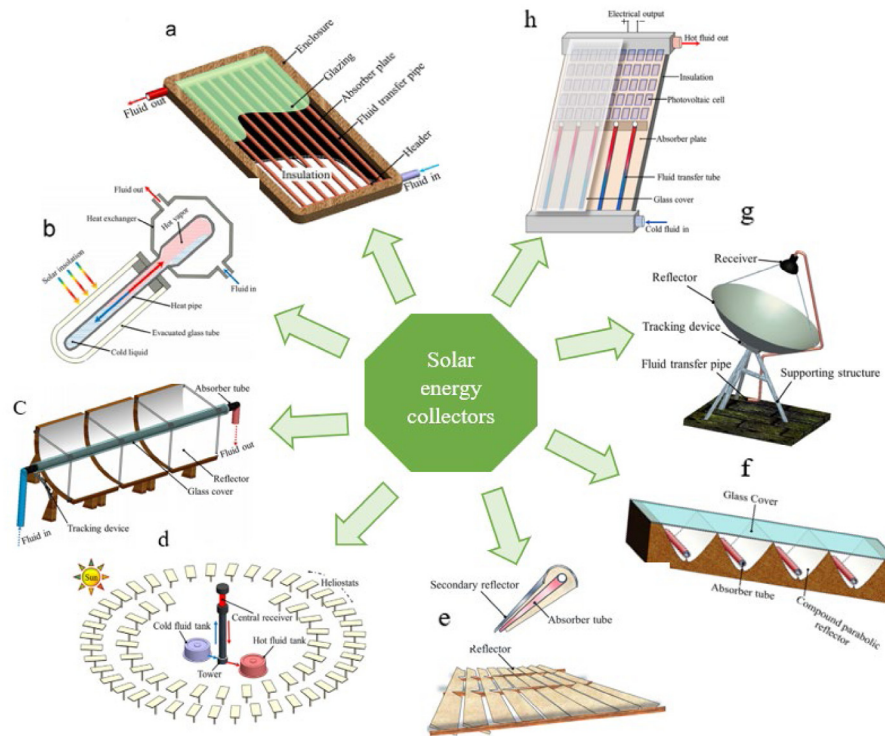


Fig. 3. Solar energy collectors (a) Flat plate, (b) Evacuated tube, (c) Parabolic trough, (d) Central tower, (e) Linear Fresnel, (f) Compound parabolic, (g) Parabolic dish and (h) PV/T system (Kumar et al., 2019).

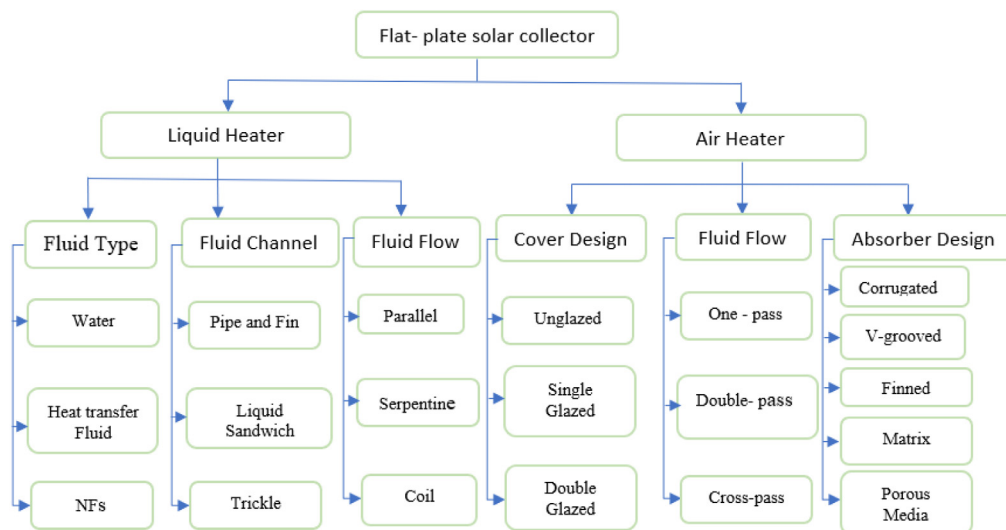


Fig. 4. Classification of FPSC (Gorjian et al., 2020).

3.1. Structure of FPSC

The main parts of a typical FPSC are the following:

- **Cover:** One or more glass sheets or other material that transmits radiation can be utilised in FPSC. The cover is a transparent blanket over the adsorbent surface used to minimise convection and radiation heating losses.
- **Riser tubes and fins:** A working fluid is heated by a groove system (riser tubes) attached to fins to increase the heat dissipation between an absorbing surface and the unit's riser tubes. Fig. 6 shows the riser tubes in the solar water or air system (Chauhan et al., 2018).
- **Absorber plate:** The absorber plate is a corrugated, flat or grooved plate surface of a conductive material (aluminium, copper, etc.) used to collect solar energy and provide heat energy to the fluid flowing in the riser tubes. The plate usually has high absorption and low emittance on its surface by coating.
- **Manifold/header:** Pipes are used to admitting and allowing discharge fluid before and after heating.
- **Insulation:** It is necessary to conduct insulation on the bottom and sides of the collector in order to decrease heat loss.

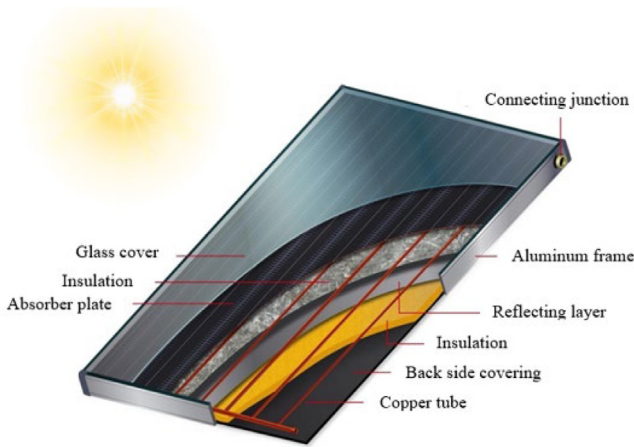


Fig. 5. Structure of FPSC.

- Casing or container: The parts that make up the FPSC are installed in a casing or cover to protect from water, dust, and other material. Fig. 5 shows the major components of FPSC.

3.2. Basic mathematical equations for FPSC

3.2.1. Mathematical formulation for efficiency calculation

The capacity of a system to transform solar energy to useful work in FPSC systems is called efficiency. The parameters that determine the magnitude of efficiency are as follow: coating, global irradiance (α , τ), type of absorber plate material, ambient temp and temp of inlet solar liquid. Whenever the rays of the sun strike the surface of a collector, the energy is transferred to a fluid and converted to useful energy according to the following equation (Kalogirou, 2009):

$$Q_{\text{loss}} = \frac{T_p - T_a}{R_L} = U_L A_c (T_p - T_a) \quad (1)$$

formula Eq. (2) used to calculate the total heat loss coefficient (U_L): (Kalogirou, 2009)

$$U_L = U_t + U_b + U_e \quad (2)$$

Top loss coefficient by Klein formula: (Klein, 1975)

$$U_t = \left\{ \frac{\frac{1}{N}}{\frac{c}{T_p} \left[\frac{T_p - T_a}{N + f} \right]} 0.33 + \frac{1}{h_a} \right\} + \left\{ \frac{\sigma (T_p + T_a) (T_p^2 + T_a^2)}{\varepsilon_p + 0.5N(1 - \varepsilon_p) + \frac{2N + f - 1}{\varepsilon_g} - N} \right\}, \quad (3)$$

where

$$c = 365.9 (1 - 0.00883\beta + 0.0001298 \times \beta^2)$$

$$f = (1 + 0.04h_a - 0.0005h_a^2) (1 + 0.091N)$$

$$h_a = 5.7 + 3.8V \quad (V \text{ is a wind velocity})$$

The following equation was used to determine the bottom loss coefficients: (Duffie et al., 1985)

$$U_b = \frac{K_b}{X_b} \quad (4)$$

The edge loss coefficient can be determined by: (Duffie et al., 1985)

$$U_e = U_b \left(\frac{A_e}{A_c} \right) \quad (5)$$

The following formula can express fin efficiency:

$$F = \frac{\tanh \left[\frac{m(W-D)}{2} \right]}{\left[\frac{m(W-D)}{2} \right]}, \quad (6)$$

where $m = \sqrt{\frac{U_L}{k\delta}}$
Mathematically,

$$F' = \frac{\frac{1}{U_L}}{w \left[\frac{1}{U_L [D + (W-D)F]} + \frac{1}{C_b} + \frac{1}{\pi D_i h_{fi}} \right]} \quad (7)$$

Heat removal factor (F_R) is defined as:

$$F_R = \frac{\dot{m} c_p}{A_c} \left[1 - \exp \left(- \frac{U_L F' A_c}{\dot{m} c_p} \right) \right] \quad (8)$$

Another equation for F_R is as follows:

$$F_R = \frac{\dot{m} c_p [T_{fo} - T_{fi}]}{A_c [I_t \tau_o \alpha_o - U_L (T_{fi} - T_a)]} \quad (9)$$

F'' : is the rate of (F_R) and (F') and can be obtained by the formula:

$$F'' = \frac{\dot{m} c_p}{A_c U_L F'} \left[1 - \exp \left(- \frac{U_L F' A_c}{\dot{m} c_p} \right) \right] \quad (10)$$

Collector plate temperature (T_p), is expressed as: (Duffie et al., 1985)

$$T_p = T_{fi} + \frac{Q_u}{A_c F_R U_L} (1 - F_R) \quad (11)$$

Q_u is the useful energy gain and can be expressed as:

$$Q_u = A_c F_R [I_t (\tau_o \alpha_o) - U_L (T_{fi} - T_a)] \quad (12)$$

Collector efficiency (η) can be calculated by the formula: (Hill, 1975)

$$\eta_c = \frac{Q_u}{A_c I_t} \quad (13)$$

$$\eta_c = F_R \left[\tau_o \alpha_o - \frac{U_L (T_{fi} - T_a)}{I_t} \right] \quad (14)$$

Thermal energy balance (energy conservation equation) is expressed as:

$$\dot{m}_p c_p \left(\frac{dT_{p,avg}}{dT} \right) + \dot{m} C_p (T_{fo} - T_{fi}) = \eta_c I A_c - U_c (T_{p,avg} - T_a) A_c \quad (15)$$

Thermal efficiency (η_c) of the flat plate solar collector is expressed as:

$$\eta_c = \frac{\dot{m} C_p (T_{fo} - T_{fi})}{I A_c} \quad (16)$$

3.2.2. Heat transfer model

Convection

The convection heat loss from the absorber to the glass cover can be calculated using the following equation: (Hollands et al., 1976):

$$Q_{\text{TC, absorber plate to glass cover}} = A_c h_{c,p-g} (T_p - T_a) \quad (17)$$

The convective heat transfer coefficient, ($h_{c,p-g}$), can be expressed by: (Hollands et al., 1976)

$$Nu = \frac{h_{c,p-g} L}{K} = 1 + 1.446 \left[1 - \frac{1708}{Ra \times \cos(\theta)} \right]$$

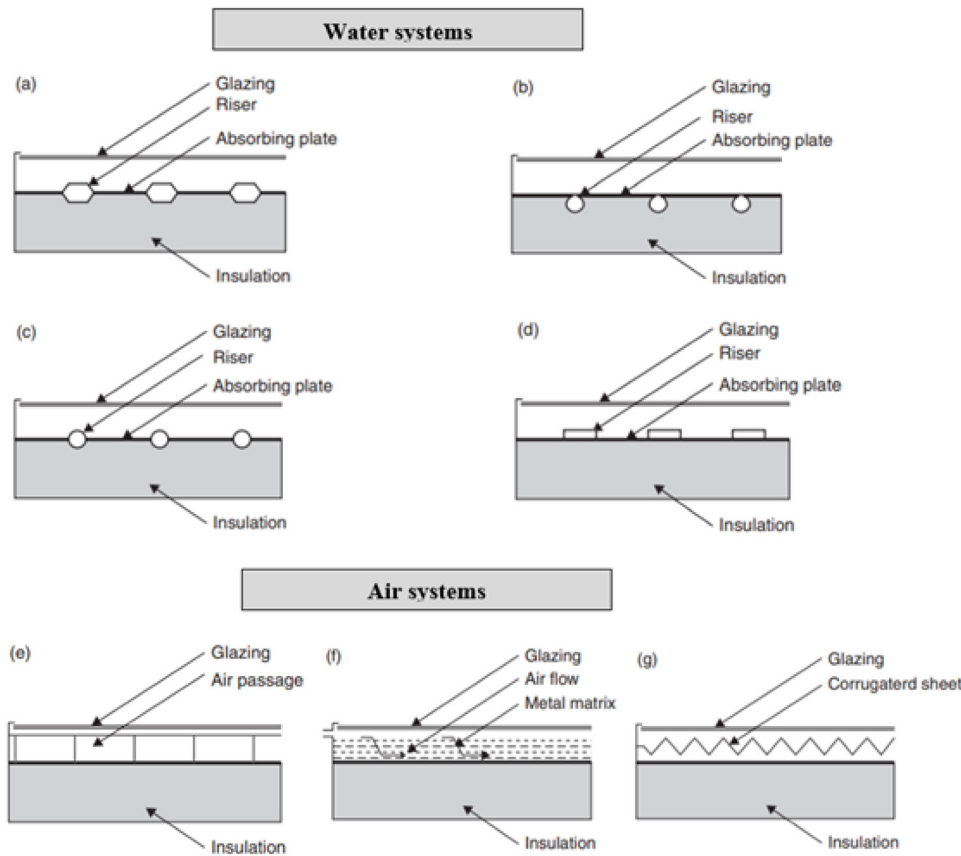


Fig. 6. Various types of FPSC absorbers for water and air (Kalogirou, 2004).

$$\times \left\{ 1 - \frac{1708 [\sin(1.8\theta)]^{1.6}}{Ra \times \cos \theta} \right\} + \left\{ \left[\frac{Ra \times \cos \theta}{5830} \right]^{0.333} - 1 \right\} \quad (18)$$

The Rayleigh number, Ra , can be obtained by:

$$Ra = \frac{g \beta' Pr}{\nu^2} (T_p - T_g) L^3 \quad (19)$$

The convective heat transfer coefficient for vertical collectors, $h_{c,p-g}$, can be calculated as: (Shewen et al., 1996)

$$Nu = \frac{h_{c,p-g} L}{K} = \left[1 + \left(\frac{0.0665 Ra^{0.333}}{1 + \left(\frac{9600}{Ra} \right)^{0.25}} \right)^2 \right]^{0.5} \quad (20)$$

Conduction

Insulation at the bottom and edges of FPSC allows heat to be conducted, where estimating the heat loss due to conduction from the collector's bottom is possible using the formula below: (Kalogirou, 2009)

$$U_{b,conduction} = \frac{K_b}{t_b} \quad (21)$$

Estimating the loss of heat conduction from the solar collector's edges should be done as follows:

$$U_{e,conduction} = \frac{K_e}{T_e} \quad (22)$$

Radiation

Any contact between two surfaces results in a radiation heat transfer in FPSC and is capable of being transmitted, reflected and absorbed. Radiation in FPSC consists of two parts.

The formula for calculating heat transfer between absorber and glass cover is as follows: (Kalogirou, 2009)

$$Q_{r, \text{absorber plate glass cover}} = \frac{A_c \sigma (T_p^4 - T_g^4)}{\left(\frac{1}{\epsilon_p} + \frac{1}{\epsilon_g} \right) - 1} \quad (23)$$

The formula to calculate the radiation coefficient between the glass cover and the absorber is found here: (Kalogirou, 2009)

$$h_{r,p-g} = \frac{\sigma (T_p + T_g) (T_p^2 + T_g^2)}{\left(\frac{1}{\epsilon_p} \right) + \left(\frac{1}{\epsilon_g} \right) - 1} \quad (24)$$

The formula to calculate the radiation coefficient between the glass cover and the ambient is found here:

$$h_{r,g-a} = \epsilon_g \sigma (T_g + T_a) (T_g^2 + T_a^2) \quad (25)$$

The network consists of convection, conduction, and radiation for FPSC as shown in Fig. 7.

3.3. Application of FPSCs

At present, solar water-heating systems (SWHS) are widely known in FPSC applications. The solar heating system utilises thermal technology to convert solar radiation from the sun into heat and transmit it to a transfer media such as air or water. This system can often replace traditional water heating systems, such as traditional fossil fuels and heating water. Small systems are used for residential water and space heating applications, while larger systems are used for industrial processes (Wang et al., 2015).

The major components of SWHS system such as the solar collector, storage tank, working fluid, pump (required in the active

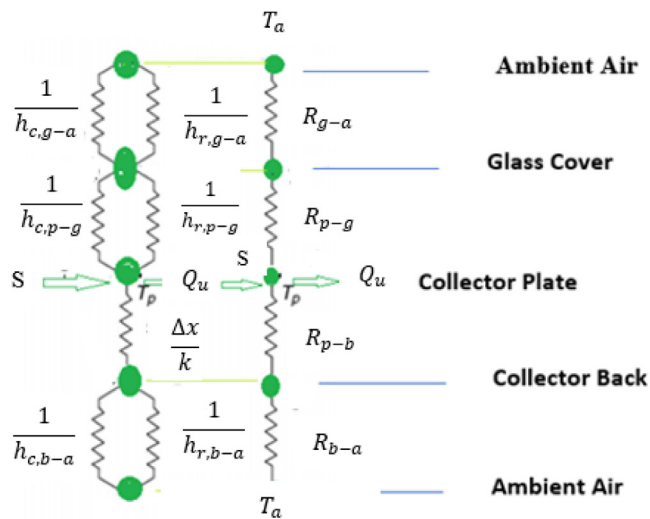


Fig. 7. Resistance thermal network for single cover FPSC.

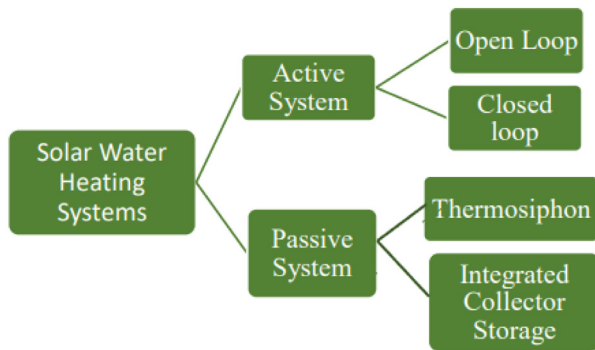


Fig. 8. Solar water heating systems.

system only), piping units, heat exchange and auxiliary heating unit (Duffie et al., 1985). The basic concept behind SWHS is that water heating involves contacting a fluid with a dark surface that causes the fluid temperature to rise while the heat is absorbed. This fluid can be induced by direct heating of water called a direct system or by heat transmission via heat exchanger called an indirect system. Fig. 8 shows the classification of the systems. In contrast, the passive system utilises the thermosiphon system and the integral collector storage system.

The active systems include fluid heater collectors, which system works using electrical pumps, controllers, and valves to move working fluids through the collectors. Forced circulation (FC) is the name given to this system, which can be used in either an open-loop mode or a closed-loop (indirect) mode (Shukla et al., 2013).

When defining the passive system, the passive solar thermal heating system must be built on two bases: Firstly, collector and storage are primarily responsible, thus combined to its structure. For illustration, rooms and windows can work as collectors properly, whereas storage can deliver moderate heat to the building structure and its content as the temperature changes. Secondly, this system does not provide moving (mechanical) fluid, but radiation absorption temperature gradients move fluid and energy. The passive system utilises the natural convection heat transfer method to flow solar liquids between the collector and the tank without mechanical devices (Shukla et al., 2013).

4. Nanofluids NFs

4.1. Concept of NFs

Traditionally, solar fluids with low thermal conductivity, such as ethylene glycol, water, and oil, have been used in industrial processes. Since the last few years, a significant amount of research has been devoted to improving heat transfer flow and advancing the applications of NFs. Choi's (1995) definition of NF pertains to a suspension of NPs (NPs) with a size of fewer than 100 nm and into a main fluid (host fluid). This technology was introduced and demonstrated for the first time by Maxwell in 1881. NPs possess characteristics that make them suitable suspension vehicles for liquids, such as small and high surface areas, low mass and high mobility. Given the NPs' tiny sizes and large specific surface areas, NFs have many superior characteristics: minimum obstruction inflows, long-term stability and homogeneity, other than having an obvious high thermal conductance. The particles are suspended in water, and no small agglomeration of a particle achieves a stable NF, thus electrical, physical or chemical techniques can do this. Commonly used dispersion techniques include ultrasonic or stator-rotor methods. Stabilisers can also be used during dispersion and are referred to as surfactants or dispersants (Wang and Mujumdar, 2007).

Recent developments in NFs have made heat transfer characteristics attractive compared with traditional heat transfer fluids. Many studies on NFs' convective heat transfer properties and thermal conductivity exist, thus solar systems are used. NFs are used in other applications such as thermal energy storage (Shin and Banerjee, 2011), solar cells (Otanicar and Golden, 2009), parabolic trough systems (Heyhat et al., 2020), solar stills (Gnanadason et al., 2012), direct absorption systems (Duangthongsuk and Wongwises, 2009), micro-channel heat sinks (Khan et al., 2021b,a), photovoltaic/thermal systems (Tian et al., 2021), circular heat exchanger (Ahmed et al., 2021), Solar thermoelectric cells (Fan et al., 2011), and Solar ponds (Singh et al., 2011), air-conditioning system (Ahmed and Khan, 2021), solar organic Rankine cycle (ORC) system (Refiei et al., 2020; Sun et al., 2021), dish solar collectors (Ouyang et al., 2021). Some researchers have investigated the use of NFs in FPSC for low-thermal applications (Angayarkanni and Philip, 2015). Their investigation found that the use of NFs is more effective than conventional solar collectors in this application, thus price economy and energy can be achievable. Fig. 9 illustrates applications of NFs in different technology areas.

In the 1970s, the concept of volumetric absorption was proposed, in which working fluid is an absorber. If used as a medium for light absorption, the working fluid must possess a high level of optical absorption. Traditional fluids still have fragile absorption properties, such as water, propylene glycol, ethylene glycol (Mercatelli et al., 2011). The use of nanofluids to absorb light in solar collectors is a recent development in solar energy. Nanofluids are composed of nanoparticles that absorb light more effectively than other fluids because of their superior optical and thermal properties, making them ideal for absorption. In addition to their many unique properties, metal nanoparticles can support a localised surface plasmon resonance (LSPR) at their surface. If free electron oscillations of the nanoparticle resonate with the incident light, this LSPR occurs. Light absorption and scattering are significantly increased due to the enhanced topical electric field in the proximity of the nanoparticles. Many studies have been carried out to optimise the light absorption of nanofluids based on the nanoparticle, size, material, volume fraction, shape, and other factors (Hussain et al., 2021; Saidur et al., 2012; Wang et al., 2017). Taylor et al. (2011) experimentally studied the optical properties of different nanoparticles, like graphite, silver, and aluminium,

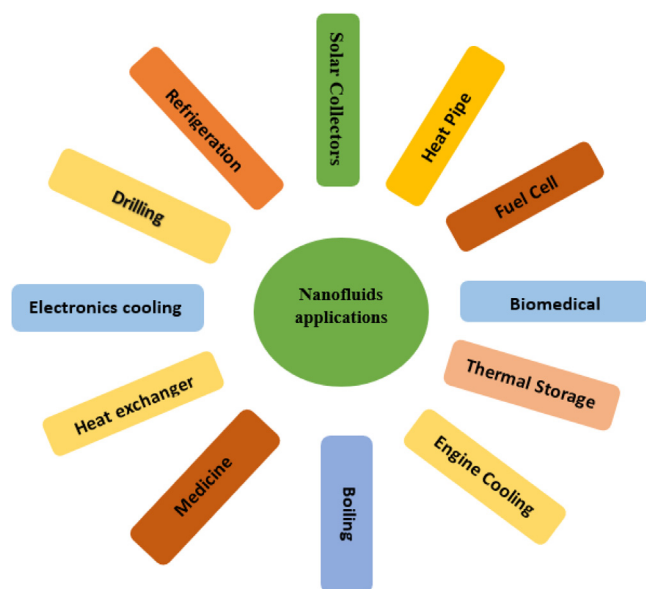


Fig. 9. NFs applications.

suspension in water as the work fluids, to measure their potential for use in solar collectors. The study found that a nanofluid with a thickness equal to 10 cm and a minimal volume equal to 0.00001 of nanoparticles can absorb approximately 95% of the light. The base fluids at longer wavelengths and the nanoparticles at shorter wavelengths were responsible for most absorption. Sani et al. (2010) experimentally investigated the light absorption qualities of nanofluids as a function of nanoparticle concentration. The properties of these nanofluids were evaluated, considering their potential use as light absorber fluids in a solar device. According to spectral transmission measurements, SWCNHs are essential in improving the fluid's photonic properties, resulting in a significant increase in light extinction even at low concentrations. It was noted that the use of SWCNHs water nanofluid as an absorber in solar devices begins to be a perfect potential step in the direction of efficiency improvement.

4.2. Classification of NF

NF is a term for describing fluids containing nanoscale dispersed particles. NF is separated into several classes according to the types of NPs (Nagarajan et al., 2014). The large classification of NPs is illustrated in Fig. 10. The transportation characteristics of NF depend on the distribution in a basic fluid of various types of NPs. Given the physical composition and chemical characteristics, NPs vary in their density and heat capacity as thermal conductivity. The two categories can be divided into single material NFs and hybrid NFs (Uddin et al., 2016).

Choi in 1995, first proposed the idea of a single-material NF and it has since become the standard form of NFs for suspension with a single type of NPs (Reddy et al., 2017). Several authors reported that nanofluids of this category perform superior because their thermophysical properties are much more favourable than their basic fluid. Hybrid nanoparticle (Hybrid NF) is an advanced nanoparticle that contains more than one type of nanoparticle (NP) and is suspended in the base fluid. In order to increase thermal conductivity, these types of nanofluids were utilised (Jana et al., 2007).

4.3. Preparation of NFs

The most pressing concern with conducting fluid NF research is obtaining a uniform distribution of NPs and keeping them uniform in size. The particles' dispersion uniformity is mainly due to the preparation method, affecting the NF's thermophysical properties. The NFs are affected more severely because they must be created using specific conditions within a liquid–solid mixture: homogeneity, physical and chemical stabilities, durability and dispersibility. The uneven distribution of the larger particles causes a very uneven distribution that alters the properties of NPs. Particle aggregates are preventing from being formed by the surfactants, dispersants and coating in the base fluid.

On the one hand, these compounds ensure consistent distribution of particles within the suspension. On the other hand, the NF's thermophysical properties can change. The NF's preparation is an essential stage in the use of NP during heat transfer. Two different ways to create NFs are identified, namely, the Single-stage Approach (bottom-up) and the two-stage Approach (top-down) (Devendiran and Amirtham, 2016).

4.3.1. Single-stage approach

Firstly, a single-stage method is followed when NPs are made and distributed in the base liquid. This process is used for NPs that may change composition or aggregate. A direct evaporation technique for creating NFs generally transforms a vapour-depositing solid solution and solidifies NPs within a base fluid. Akoh et al. (1978) devised the vacuum evaporation onto an able to run oil substrate (VEROS) technique for one-step direct evaporation, which refers to a single-stage procedure that can produce evenly distributed NPs in the fluid. This method eliminates the need for NP processing such as dispersion, drying, transportation and storage. One disadvantage of the method is that concentrated contaminants remain in the NFs, thus challenging to separate impurities from NFs. Using a single-stage preparation of NPs in a uniformly distributed condition, the particles are not likely dispersed and using this method is its nonproduction of pure metallic nano powder and the difficulty of contaminant disposal (Wagener et al., 1997; Eastman et al., 1997). Fig. 11 shows the single-stage preparation for NFs.

4.3.2. two-stage approach

The two-stage process is a widely used technique to prepare NFs. The dry fine particles of NPs, nanofibers, nanotubes, etc. are produced initially with physical and chemical methods. NPs are distributed to the base fluid using ultrasonic vibration, magnetic disturbing of energy, shear mixing, homogenising ball milling and NPs. The two-stage method is often used because it is cheaper, and the materials are commercially readily available. Researchers say that the two-stage process is usually considered the best choice for bringing NPs of oxide NPs (Babar and Ali, 2019).

The major drawback of the two-stage method is that NPs can form clusters during preparation, hence avoiding NPs' proper synthesis within the conventional fluid. Dry NPs tend to be added together due to maximum surface movement and surface area. The most common way to improve the NPs' stability in thermal transmission fluids is by adding surfactants (Arshad et al., 2019). The two-stage preparation approach for NFs is shown in Fig. 12.

4.4. Thermophysical properties of NFs

NP's thermal properties are fundamental to the performance of the NFs. The properties of the base fluid, such as viscosity, pressure drop, thermal conductivity, and specific heat, are affected by the addition of NPs. Some of the key factors which change thermophysical properties are the concentration of NPs,

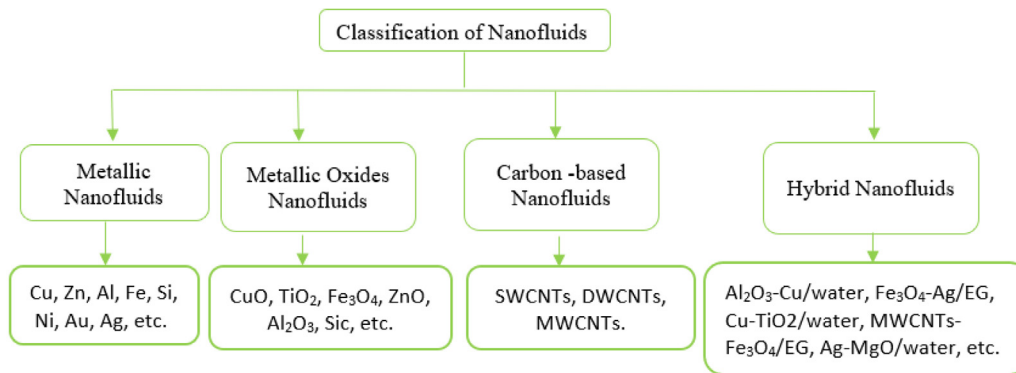


Fig. 10. Classification of NF.

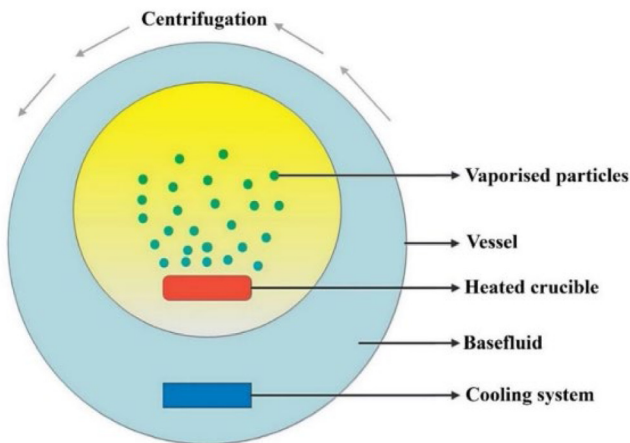


Fig. 11. Description of the single-stage approach (Almurtaji et al., 2020).

shape, size of NPs and purity of NPs. The solar collectors' thermal performance primarily depends on their thermal behaviour. Temperature variation, ambient conditions, basic fluid type, NP size, shape and volume concentration are the operating parameters. In consideration of all parameters, selecting the proper NF is necessary to optimise the results (Eggers and Kabelac, 2016).

4.4.1. Thermal conductivity analysis

There are two critical parameters for assessing fluid heat transfer rate in turbulent and laminar fluid conditions: Nusselt and Prandtl numbers. These numbers influence the fluids' thermal conductivity. Therefore, the heat transfer potential of NF is necessary to be known for the thermal conductivities (Eastman et al., 2001). Table 2 shows some of the most common thermal conductivities of NPs and base fluids. One factor that contributes to an improvement in thermal effectiveness is the Brownian movement, as illustrated in Fig. 13a, which regulates the thermal behaviour of the dispersion of fluid-NPs (Han et al., 2016). Second factor for the increase in thermal efficiency by the liquid molecules forming layered structures around the NPs called the nanolayer, as shown in Fig. 13b. In addition, heat is conveyed in crystalline solids by randomly formed phonons that spread randomly and are dispersed via defects or collisions. Furthermore, particle clustering affects effective thermal conductivity because localised areas of high particulate matter are created from settling particulate agglomerations with less thermal flow resistance (Kebblinski et al., 2005). Table 3 provides examples of some additional models developed by different effective thermal conductivity correlations.

Table 2

Commonly of thermal conductivities of NPs and base liquids Tawfik (2017a,b,c).

Particle	Thermal conductivity (W/m K)
Carbon Nanofibers	13
Silver (Ag)	424
Graphite	2000
Titanium dioxide (TiO ₂)	8
Iron (Fe)	80
Steel	46
Stainless Steel	16
Alumina (Al ₂ O ₃)	40
Carbon Nanotubes	2000
Iron Oxide (Fe ₂ O ₃)	7
Aluminium (Al)	273
Zinc Oxide (ZnO)	29
Amorphous Carbon	1.59
Diamond	900–2320
Gold (Au)	315
Cupric Oxide (CuO)	77
C60–C70 (Fullerenes)	0.4
Copper (Cu)	398
Base liquid	
Ethylene Glycol	0.25
Water	0.608

Table 3

Various thermal conductivity models of NFs are available in the works of literature.

References	Thermal conductivity models
Maxwell (1881)	$K_{nf} = \frac{2K_{bf} + K_p + 2\phi(K_p - K_{bf})}{2K_{bf} + K_p - \phi(K_p - K_{bf})} K_{bf}$
Hamilton (1962)	$K_{nf} = K_{bf} \left[\frac{K_p + (n-1)K_{bf}(n-1)\phi(K_{bf} - K_p)}{K_p + (n-1)K_{bf} + \phi(K_{bf} - K_p)} \right]$
Yu and Choi (2004)	$K_{nf} = \frac{K_p + 2K_{bf} + 2(K_p - K_{bf})(1 + \beta)^3\phi}{K_p + 2K_{bf} - (K_p - K_{bf})(1 + \beta)^3\phi} K_{bf}$
Timofeeva et al. (2007)	$K_{nf} = K_{bf}(1 + 3\phi)$
Bhattacharya et al. (2004)	$K_{nf} = \phi K_p(1 - \phi)K_{bf}$
Xue (2005)	$K_{nf} = K_{bf} \frac{1 - \phi + 2\phi \frac{K_p}{K_p - K_{bf}} \ln \frac{K_p + K_{bf}}{2K_{bf}}}{1 - \phi + 2\phi \frac{K_{bf}}{K_p - K_{bf}} \ln \frac{K_p + K_{bf}}{2K_{bf}}}$
Mintsa et al. (2009)	$K_{nf} = K_f(1.75\phi + 1)$

Many theoretical and experimental work has been done to study the thermal conductivity of NFs. There are many experimental measurements to measure the thermal conductivity of

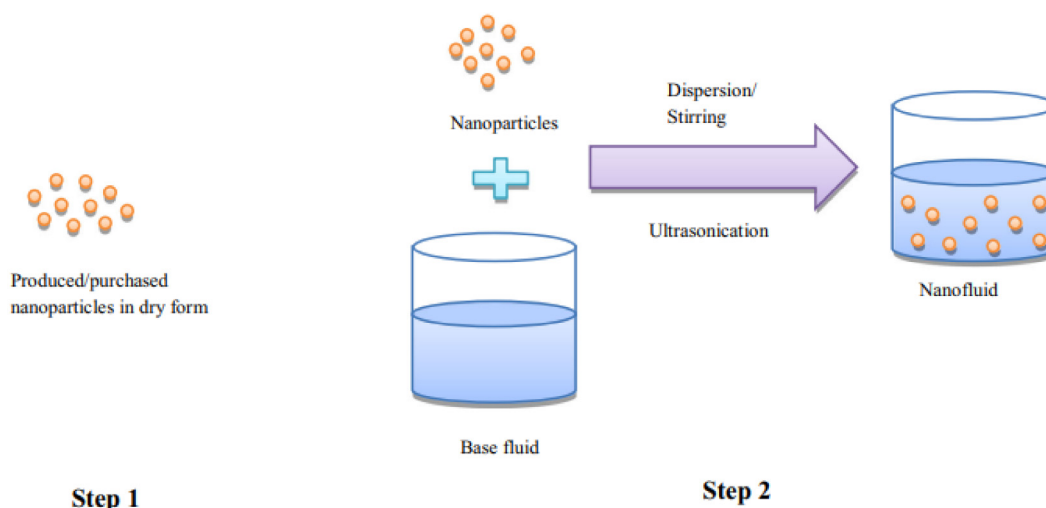


Fig. 12. Description of the two-stage approach (Arora and Gupta, 2021).

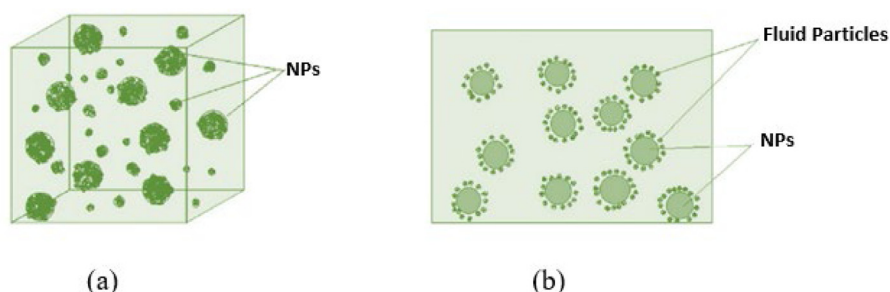


Fig. 13. (a) Brownian motion of NPs and (b) NF body is made up of NPs, fluids in large volumes and nanolayers at the link between solid and fluid (Gupta et al., 2017).

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nanofluids, including: 3 W method, transient hot-wire process, thermal constants analyser, optical beam deflection technique, and temperature oscillation method (Suresh et al., 2011). Among these technologies, the constant thermal analyser is the most advantageous method used by many researchers (Liu et al., 2005).

Zhu et al. (2009) tested the pH-value variation effect of Al_2O_3 – H_2O NF's thermal conductivity. According to the study results, pH strongly influences the thermal conductivity of Al_2O_3 – H_2O NFs and the various concentrations of nanosuspension SDBS dispersants. By adding an optimised SDBS dispersant, thermal conductivity was improved. Saidur et al. (2011) experimentally investigated the performance of thermal conductivity using Fe_3O_4 nanofluids. The experiment was carried out considering the temperature range of 20–60 °C and concentration of 0.0%–2.0%. The thermal conductivity was found to increase with increasing concentration of NPs by 48% at a concentration of 2.0% and at 60 °C.

4.4.2. Viscosity analysis

The viscosity is a fundamental property of a fluid that provides frictional resistance to shearing stresses through the adjacent fluid layer. It can also be defined as the ratio of shear stress to shear rate. Viscosity plays a crucial role in turbulence or laminar flow through every duct since pressure decrease is proportional to the viscosity-proportional Reynold numbers. With an increase in solid volume and weight percent of NPs, the viscosity of NFs usually increases and decreases by increasing temperature (Chandrasekar et al., 2010). Due to the non-Newtonian NF behaviour, the increase in viscosity is not linear. The increment of fluid viscosity increases the pressure losses, and the pumping power demand would increase consequently. NPs concentration, base

fluid viscosity, particle diameter, pressure, shear rate, particle type, pH value, particle shape and temperature are the main factors influencing effective viscosity (Heris et al., 2006). Several viscometers were used to measure NF viscosity, such as a rotational rheometer, capillary tube viscometer, vibro-viscometer, cup-type viscometer and falling ball/falling piston viscometer. The most common devices used for viscosity measurements of NFs are, among others, capillary tube viscometer, piston-type rheometer, and the rotational rheometer. Several models were developed; thus, many experiments were conducted to assess viscosity predictions using analytical models. The list of models to measure NF viscosity obtained from the researchers is given in Table 4.

Chen et al. (2008) experimentally measured the impact of volume fraction and temperature with distilled water over a 5 °C – 65 °C temperature range on the multiwalled carbon nanotubes (MWCNT) viscosity. Viscosity increases with NP load when the volume fraction is above 0.4 vol%, and the relative significantly increases under a temperature of 55 °C. Wang et al. (1999) studied the relative viscosity of Al_2O_3 –water and Al_2O_3 –ethylene glycol NFs. Results showed that the relative viscosity increases as the volume fraction for both NFs increases. Thus, the desired heat transfer increase is compensated by the unwanted pressure drop increase. Nguyen et al. (2008) examined the effect of temperature and particle concentration on the dynamic viscosity of water Al_2O_3 NFs with 47 nm and 36 nm particle sizes. The results showed that the dynamic viscosity of NFs increased considerably at volume fraction from 1% to 9.4% and decreased with a temperature increment of 22 °C to 75 °C. The relative viscosity obtained

Table 4
Various viscosity models of NFs available in works of literature.

References	Viscosity models
Einstein (1906)	$\mu_{nf} = \mu_{bf}(1 + 2.5\phi)$
Brinkman (1952)	$\mu_{nf} = \mu_{bf} \frac{1}{(1 - \phi)^{2.5}}$
Lundgren (1972)	$\mu_{nf} = \mu_{bf} \left[1 + 2.5\phi + \frac{25}{4}\phi^2 + 0\phi^3 \right]$
Batchelor (1977)	$\mu_{nf} = \mu_{bf}(1 + 2.5\phi + 6.5\phi^2)$
Frankei and Acrivos (1967)	$\mu_{nf} = \mu_{bf} \frac{9}{8} \left[\frac{\left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}}{1 - \left(\frac{\phi}{\phi_m}\right)^{\frac{1}{3}}} \right]$

for Al₂O₃–water in the ambient and particulate volume fraction was ranged from 0.15% to 13%.

Yu et al. (2009) studied the NFs containing ZnO NPs based on the viscosity of EG. Results show that ZnO-EG NFs show Newtonian compatibility with low volume ($\phi \leq 0.02$), while viscosity decreases significantly when the temperature increases. NFs showed non-Newtonian behaviour at higher volume concentrations ($\phi \geq 0.03$) because of a higher aggregate volume fraction. Mena et al. (2013) reported effective Al₂O₃/water NF viscosity measurement and evaluated the viscosity and range of temperatures from 5 °C to 20 °C for heat transfer simulation applications of Al₂O₃–water NFs with particulate volume fractions below 1 vol%. These experimental results showed that the NFs viscosity is consistent with most of the corresponding extrapolated values within the low temperature and volume fractions.

4.4.3. Density analysis

Density is another essential thermophysical property to assess the NFs heat transfer performance. NF density is proportional to the system's solid (NPs) and liquid (base fluid) volume proportion. When the solid density is higher than that of fluids, NF density generally increases as NPs are added to the fluid and affects the number of friction factors number, pressure loss, Reynolds number and Nusselt number (Bock Choon Pak, 2013). The measurement results indicate that the theory of mixture can accurately estimate the NFs' density using the following equation:

$$\rho_{nf} = (1 - \phi) \rho_{bf} + \phi \rho_p$$

A limited correlation between the particle size, particle shape, temperature of NFs, surfactants and base fluid effect for effective density is observed. Therefore, more work is required to ensure that the effective density at higher particle concentrations is predicted with great precision.

Ganeshkumar et al. (2017) studied the forecast of the CuO/water NF density, but no results were compared with the equation. The concentration was also predicted to increase, but that the temperature decreased. Teng and Hung (2014) determined alumina density (Al₂O₃)/water NF. The outcomes show that the density variation in the density with the equation is between 1.50%–0.06% and 0.25%–2.53%. The calculated density results were further differentiated as the NF particle load increased. The experimental results were found to be in a reasonable range of two different types of densities.

The literature body shows that NF density experimental studies are very few. Therefore, further research is needed to determine the conditions under which the theory mixing equation produces the best results. In addition, the correction factor and correlations need to be determined depending on the NF variation, particle size, temperature, particle load, etc., to achieve the exact density values.

Table 5
Various specific heat models of NFs available in works of literature.

References	Specific heat models
Bock Choon Pak (2013)	$C_{pnf} = \phi C_{pp} + (1 - \phi)C_{pbf}$
Ghazvini et al. (2012)	$C_p = 2.62 - 6 \times 10^{-3}T + 2 \times 10^{-5}T^2$
Xuan and Roetzel (2000)	$C_{pnf} = \frac{\phi \rho_p C_{pp} + (1 + \phi)\rho_{bf} C_{pbf}}{\rho_{nf}}$
Zhou and Ni (2008)	$C_{pnf} = \frac{(1 - \phi) \rho_f C_{pf} + \phi \rho_p C_{pp}}{\phi_f \rho_f + (1 - \phi)\rho_p}$
Fakoor Pakdaman et al. (2012)	$\frac{C_{pbf} - C_{pnf}}{C_{pbf}} = (0.0128 \times T + 1.8382)\phi^{0.4779}$

4.4.4. Specific heat analysis

The specific heat plays a predominant role in influencing the rate at which NFs are transferred. It is the amount of heat required to raise the temperature of 1 g of NF by 1 °C. The specific heat of materials is a significant property to determine their thermal performance. The specific heat remains constant at constant pressure and with a wide variety of temperatures for conventional materials. The specified NF heat can vary depending on the nanomaterial type, temperature, base fluids and NP concentration in basis fluids. Calorimeters measure the specific heat of the NFs. Differential scanning calorimetry (DSC) is a powerful tool for the determination compared with a standard reference sample of known specific heat Sadeghinezhad et al. (2016). Table 5 lists the different specific heat models and explains the works of literature.

Saeedinia et al. (2012) examined the specific heat capacity of 0.2%–2% CuO-base oil NFs at different temperatures with particle weight fractions. In this experiment, NFs have shown a less specific heat capacity than base fluid and decreased with an increased NPs concentration. The result further showed that the specific heat of 2 wt% NFs was approximately 23% lower than that of the base fluid at 40 °C. Zhou et al. (2010) studied the CuO NF specific heat capacity decrement by 1.16%–5% with base fluid EG for volume fraction 0.1%–0.6%, with a 25 nm–500 nm particle size. Some NFs have an abnormal volume-concentration behaviour. Starace et al. (2011) stated that SiO₂ NPs special heat capacity in EG base fluid decreased and increased. Shahrul et al. (2014) conducted a comparative study on NF-specific heat for energy applications. They found that the specific heat decreases as the volume fraction of most nanomaterials in base liquids increases. Zhou and Ni (2008) presented a study with a differential calorimeter scanning on the specific heat of water-based Al₂O₃ NF. The results show that NF specific heat is progressively decreasing as the concentration of NPs increases. The relation between them shows a good consensus on the thermal balance model prediction, while the simple mixing model does not predict the NFs heat.

4.4.5. Convective heat transfer analysis

The performance characteristics of NFs are intrinsic considering the convective heat transfer parameters such as Nusselt number, Reynold numbers, Prandtl numbers, Peclet number and convective heat transfer coefficients. The thermal performance of these parameters is determined by volume fraction, particulate size and the base fluid type and by operating conditions, such as temperature, flow passage and flow type.

Heris et al. (2006) studied water with NPs Al₂O₃ and CuO under laminar flow (up to turbulence and found that the increased heat transfer with Al₂O₃ particles was up to 40%, while the increased heat conductivity was below 15%. Putra et al. (2003) introduced experimental observations for the natural convection within the horizontal cylindrical cylinder of two oxides (Al₂O₃)-water-based NFs (CuO). Forced convection results revealed that

the natural convective heat transfer depends on particulate concentration, density and aspect ratio of the cylinders had systematically and deteriorated. No clear reason for this effect was reported. The role of the slip and sedimentation of particulate liquids appears to be important and needs further study in the future. The decay was more significant for CuO NFs and increased with particle concentration. Wen and Ding (2004) studied the effect of the volume concentration of Al_2O_3 on the heat transfer coefficient. It was found that HTC increased by 47% for 0.6%–1.16% volume by 26 nm–56 nm particle size. Xuan and Li (2003) reported that CuO/water NF heat transfer improved by 0.3% to 2% with laminar and turbulent flow regimes. A correlation was derived for the Nusselt number. Experimental studies carried out by several researchers showed improvement in convective heat transfer parameters, coefficient convective heat transfer and volume increase in Nusselt numbers.

4.4.6. Pressure drop analysis

Experimental and theoretical studies on NF pressure drop are limited. Sajadi and Kazemi (2011) investigated TiO_2 /water NF turbulent heat transmission behaviour in a circular tube under a fully developed turbulent system for different volumetric concentrations. Their measurements showed that the NF pressure drop was slightly higher than the base fluid and increased as the volume concentration increased. Razi et al. (2011) experimentally investigated the NF cubic-base oil pressure drop and thermal properties under laminar flows at constant heat flow in flattened tubes. A notable increase in thermal transfer coefficient and pressure decreases in NFs compared with base fluids when achieved in each flattened tube and the same flux conditions. NFs have better transmission characteristics when flowing in flattened pipes instead of round tubes. For the flow of NF at two wt% concentration within the round pipeline and flattened tubes of 8.3 mm and 6.3 mm internal tubes, the maximum amounts of heat transfer are 16.8%, 20.5 and 26.4%. Suresh et al. (2012) tested the hybrid NF pressure drops in the tube under different isothermal conditions at different fluid flow rates for laminar flow. The measured pressure drop (Δp) is used to calculate the friction factor in the entire test section. The laminar flow number of Reynolds for Al_2O_3 –Cu/water hybrid NF was examined for friction factor variations. The results showed that 0.1% Al_2O_3 –Cu/water hybrid NFs show a slightly higher friction factor than 0.1% Al_2O_3 /water NF because of its higher viscosity than Al_2O_3 /water NF. The average friction factor increases of 0.1% is 16.97% compared with water for the Al_2O_3 –Cu/Water hybrid NFs. Al_2O_3 /water NF showed an average increase of 6% in the friction factor for the same volume concentration, indicating that a further pumping power penalty is incurred compared to Al_2O_3 /water hybrid NFs, as opposed to Al_2O_3 /Water.

4.5. Stability of NFs

NF stability plays the most important role in improving the performance of every system. NPs have tremendously small sizes and high kinetic energies because of Brownian motion. Despite their extremely large sizes and stability, they do not remain suspended. NPs settle from the solution with time under the gravity influence. NFs have poor stability due to the interaction of the particles and between them and the surrounding liquid, which influences the NFs commercialisation (Sezer et al., 2019). This sort of behaviour can be linked to two opposing forces: (a) the well-known Van der Waals attraction on the part surface, which attracts particles to each other and then forms clusters or agglomerations and settles at the bottom by gravity and (b) the repulsive electric double layer, which tends to reverse the force of gravity, steric and electrostatic mechanisms of repulsion,

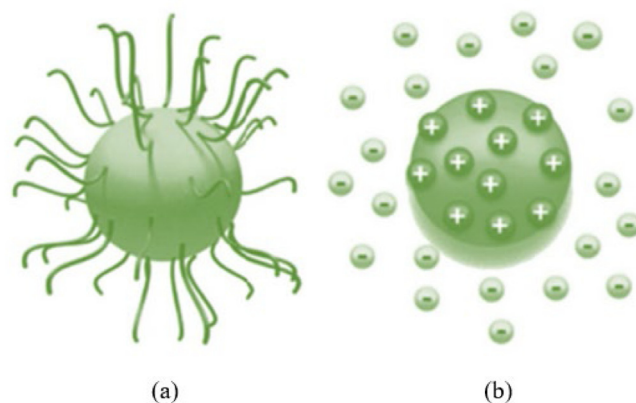


Fig. 14. Mechanisms of repulsion (a) steric and (b) electrostatic (Mukherjee and Paria, 2013).

as shown in Fig. 14. From a practical point of view, clustering, and sedimentation cause two difficulties. Firstly, the photothermal and thermal properties of the NF are lost. Secondly, the sediment accumulation in solar collectors, causing clogging. Sediments cause abrasion of the wall tube, and sediments accumulate to reduce flow. Stability is an essential aspect of NF marketing as it extends the product's shelf life while maintaining its thermophysical qualities. The repulsive force of the electric double layer should exceed the attractive forces of the Van der Waals to achieve a stable NF. Therefore, the stability and performance of the NFs are essential to maintain dispersed NPs. For applications, the long-term stability of NFs is crucial. To improve stability and reduce the concentrations and sedimentation of NPs, researchers used various techniques. NFs' long-term stability and thermal properties were supported by chemical methods (addition of the surfactants, pH adaptation and surface modification) and physical methods (ultrasound agitation, homogenisation and ball milling).

5. Methods to enhance NF stability

5.1. Chemical treatment methods

The NPs and base fluid nature determine NF stability. For example, oxide NPs are hydrophilic, while CNTs are hydrophobic. Water is also polar as base fluid, and oil is nonpolar. Adding surfactants or changing the particle surfaces can improve NPs' dispersion into base fluids, such as the CNTs dispersion into the water and oxide particles into the oil (Yu and Xie, 2012).

Surfactants are surface-active substances that link the NPs and the base fluids to avoid the particles aggregation. Adding acids or bases can keep the pH of the length solution from its isoelectric point (IEP) that increases colloidal suspension stability. The surface modification applied to the NPs before being dispersed into the base fluid is another method of chemical stabilisation. The following sections briefly discuss these methods.

5.1.1. Addition of surfactants

Surfactants are among the most diversified chemicals, detergents, pharmaceutical products, mud boilers, froth flotation and dispersants. Surfactants addition is an effective method to increase stability, which prevents NF agglomeration of NPs (Byrne et al., 2012a) and a simple and cost-effective chemical method that reduces base fluid surfaces and improves NP immersion. Oil-soluble and water-soluble surfactants can be classified. The surfactants are composed of a hydrophobic tail (e.g., hydrocarbons with long-chain) and the hydrophilic polar heads, which



Fig. 15. Ultrasonics types. (a) Probe (b) Bath.

tend to increase their hydrophilic behaviour between the base fluid and the NPs. The surface charges of NPs and the type of used base fluid primarily determine which surfactant is chosen. Based on the head composition, the dispersant can be grouped into four classes: (1) the negative charge head group of ionic surfactants (e.g., long-chain fatty acids, alkyl sulfates, sulfonates and sulfosuccinate), (2) the neutral head group nonionic surfactants (e.g., polyethylene oxide, alcohols and other polar groupings), (3) the positive charge head group of cationic surfactants (e.g., long-chain quaternary ammonium compounds and long-chain amines) and (4) amphoteric surfactants of zwitterionic headgroups (charge is a pH-dependent) (Tawfik, 2017a). Several surfactants are commonly used in the NFs research such as polyvinylpyrrolidone (PVP), sodium dodecyl sulphate (SDS), oleic acid (OA), hexadecyl trimethyl ammonium bromide (HCTAB), Poly (acrylic acid sodium salt), Sodium dodecyl benzene sulfonate (SDBS) and dodecyl trimethylammonium bromide (DTAB) (Tiara et al., 2017). The bases fluid used in the preparation of NFs is the determinant for an appropriate surfactant. In general, a water-soluble surfactant should be used when the base fluid is a polar solvent, otherwise an oil-soluble one. The hydrophilic/lipophilic balance (HLB) value can estimate the solubility of nonionic dispersant. The higher the HLB value, the more water solutions the surfactant, while the lower the HLB value, the higher the surfactant's oil solubility. The disadvantage of the NF stabiliser dispersant is its sensitivity to hot temperatures because the increased temperature causes damage to the bonds between the NPs and the surfactant and can chemically respond in the production of foams in certain cases (Chen et al., 2008). In addition, excessive surfactants affect the thermophysical properties of the NF, increasing the NF's viscosity and reducing its thermal conductivity.

Byrne et al. (2012b) tested NFs prepared with and without CTAB CuO/DW. Three nano powder CuO concentrations of 0.005 vol%, 0.00 vol%, and 0.1 vol%, were employed to produce the suspensions with and without surfactant at 1: 1 vol%. Dynamic light dispersion (DLS) measures showed a rise in particle concentration agglomeration when 0.1 vol% sample containing no surfactant showed that the particle size dropped rapidly from approximately 3000 nm at times zero to 300 nm at 4 o'clock. The researchers explained the decrease in particle size by leaving the smaller particles unfree to be detected by the colonisation of heavier agglomerates of particulates. The surfactant samples obtained an average particle size of 200 nm with no disparity for 7 days.

5.1.2. Surface functionalisation of NPs

This method is functionalised before being dispersed in the base fluids on the surface of NPs or nanotubes. Surfactants can

enhance stability, but NF's performance can be reduced through difficulties such as contamination, moulding and thermal properties loss (Ghadimi et al., 2011). Surfactant-free surface functionalisation provides long-term stability to NFs without the problems typically associated with surfactant materials. To obtain a self-stabilised NF, functionalised NPs are incorporated into the base fluid. In general, appropriate organic function groups are chosen as they attach to the atomic surface to make it possible for NPs to auto-organise themselves and avoid agglomeration (Neouze and Schubert, 2008). The literature reports several approaches. For example, Kulkarni et al. (2006) studied copper oxide (CuO) where NPs functionalisation was examined.

5.1.3. pH control of NF stability

Control of NP surface charge by regulation of fluid pH is a technique that can increase NF stability. The generation of a high surface charge creates an electrical dual layer around the NP, resulting in powerful Coulombic forces promoting particle dispersion. Zeta manipulation is a method for improving the stability of the colloidal dispersion. When the pH of the solution is far from the isoelectric (IEP) point where the surface charges of the particles and the zeta potential are zero, the NPs are more stabilised (Choudhary et al., 2017). Manipulation of NF pH value changes NP surface and can significantly improve the dispersed NPs stability (Ghadimi et al., 2011). The stability of NF is caused by directly connected electrokinetic properties. Therefore, by changing the NFs pH value, the zeta potential value of NFs is obtained. The pH's suspension is normally needed as neutral since alkaline or acidic solution can increase or decrease the pH of the NF and cause heat transfer surfaces to corrosion and NPs to dissolve. Several studies have been conducted to show the effect of pH on NF stability.

Yoo et al. (2007) studied pH effect on alumina (Al_2O_3) and Cu-based aqueous NFs dispersion stabilisation. Sodium dodecylbenzene (SDBS) was used for the study as a surfactant. In contrast, the pH value of the respective NFs was determined by adding either hydrochloric acid (HCl) or sodium hydroxide (NaOH). The viscosity of aluminium fluids was generally greater for the same weight fraction and pH value than Cu-based fluids. The study showed that dispersed and stable NFs were produced (alumina-based: between 7.5 and 8.9; Cu-based: 7.6). However, the pH was lower than seven, resulting in both unstable NFs in the agglomeration and rapid sedimentation. Yang et al. (2001) tested NFs that have been loaded by the rheological behaviour of TiO_2 when the pH value was different. This study investigated the effect on the viscosity for a 54.5 wt% (24 vol%) TiO_2 , (mean 0.24 μm particulate size) nano-fluid of varying the pH between 1.2 and 9.1. The maximum viscosity levels were recorded for pH values between 5 and 6.5, whereas NFs with a pH value of nine were observed with less viscosity.

5.2. Physical treatment method

This method uses high energy to break the cluster of NPs and create a well-dispersed colloidal suspension by homogenisation, ultrasonication and ball milling. The surfactants are generally added to avoid NP reagglomeration.

5.2.1. Ultrasonication

Ultrasonic baths/probes are usually used to disperse clusters of NPs physically. Fig. 15 shows both types. Probe sonication of the physical treatment methods is used most often for NFs stabilisation. A programmed period is used to disperse NPs into base fluids and break up NPs clusters (Ganesan et al., 2016). Sound energies at the ultrasonic level are at 20 kHz and above. For various intervals, researchers used ultrasound at various levels of

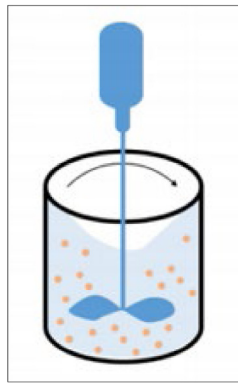


Fig. 16. Homogeniser (Sezer et al., 2019).
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power and frequency. Optimum sonication conditions can differ with different parameters such as particulate concentration, particle size, type of particle, type of fluid base, etc. Many scientists have employed ultrasonic in the preparation and stabilisation of NFs. Mahbubul et al. (2016) studied ultrasonic time influence on water-based Al_2O_3 NF stability. Better colloidal dispersion and lower viscosity were detected by increasing the sonication time.

5.2.2. Homogenisation

Homogenisers of high shear in Fig. 16 are used to break the clusters of NPs existing in the colloidal solutions. Hwang et al. (2008) studied that different techniques are used to stabilise the NF samples, such as ultrasonic bath, ultrasonic disrupter, stirrer and high-pressure homogeniser. The colloid size was measured to examine the particle agglomeration in the suspensions. A high-pressure homogeniser as an efficient tool for breaking down the NP agglomerates was suggested.

5.2.3. Ball milling

Another method for dispersing/disengaging the NPs and the nanotube into the basic fluids is ball milling. The planetary ball mill diagram is shown in Fig. 17. Although ball milling is the least studied method in stabilisation, numerous researchers reported that it effectively obtains well-distributed suspensions. Farbod et al. (2015) investigated synthesised NFs with CuO NPs in engine oils. Oil, NPs and grinding balls were placed in a container and milled by a laboratory-sized planetary factory for three hours. The balls were made of stainless steel with a one-centimetre diameter, and the balls weighing ratio to the NF was 7:1. The NFs were very stable after milling, and no sedimentation for over 30 days was observed. Furthermore, no changes in NP morphology have been observed.

6. NF stability evaluation methods

The stability of NF is essential during the long period, but solid phase NPs are in constant Brownian motion and can interact earlier (or later) with their neighbours. During these interactions, strong attractiveness forces create the aggregation of particles. The agglomerations gradually increase and start to become unstable under gravity. NFs become unstable. The sedimentation process also reduces the thermal performance of NFs in addition to blocking flow channels in the collectors. Therefore, assessing the long-term stability when a NF is produced is important. No current standard method for measuring the stability of NFs exists. Visual inspections (sedimentation) and zeta potential are the most extensively used techniques for analysing suspension

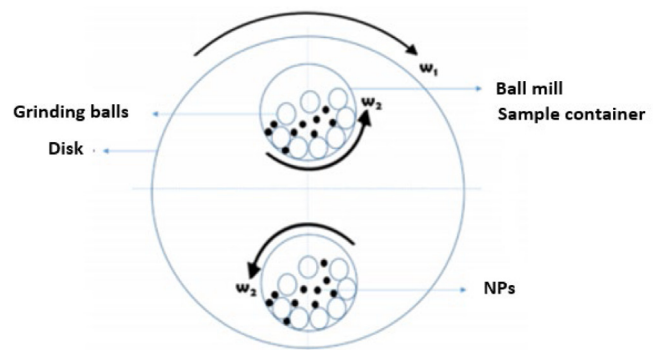


Fig. 17. Schematic of ball mill (Sezer et al., 2019).
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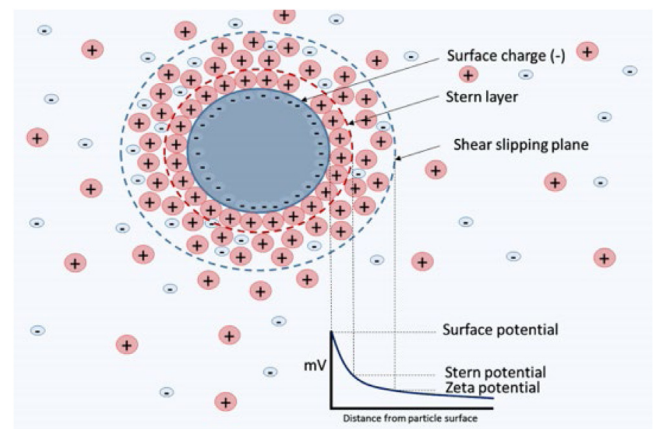


Fig. 18. Schematic of Zeta potential (Sezer et al., 2019).
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stability. Some studies showed the results of zeta potential analysis, while others have only reported stability through visual inspection. The following sections discuss different methods used to assess the stability of NFs.

6.1. Zeta potential measurements

NF stability can be determined by measuring the electrical potential between the dispersed medium and the fixed fluid layer attached to the particle. Zeta potential (ζ -potential) is a key indicator of colloidal dispersion stability. Zeta is the possible difference between the NPs' surface and the stationary fluid layer attached to NPs, as shown in Fig. 18. Zeta potential magnitude designates the electrostatic repulsion extent between nearby and equally charged particles in a dispersion. High zeta potential NFs are electrically stabilised (negative or positive), while low zeta potential NFs are unstable (Chen and Xie, 2010). The method used for evaluating suspension stability is the Zeta potential test. The effect on the stability of water-based NFs by pH and sodium dodecylbenzene sulfonate (SDBS) by a zeta potential analyser (Daungthongsuk and Å., 2007) has been investigated. The zeta potential measurements by Fourier transformation infrared spectrum were used to study the adsorption of surfactants (Wang et al., 2009). Zeta potential was aqueous silica NF stability.

6.2. Sedimentation method

This is one of the easiest methods to measure NF stability. In this approach, an external force monitors the volume of agglomerated NPs in the nanofluid. The sample is placed in a transparent

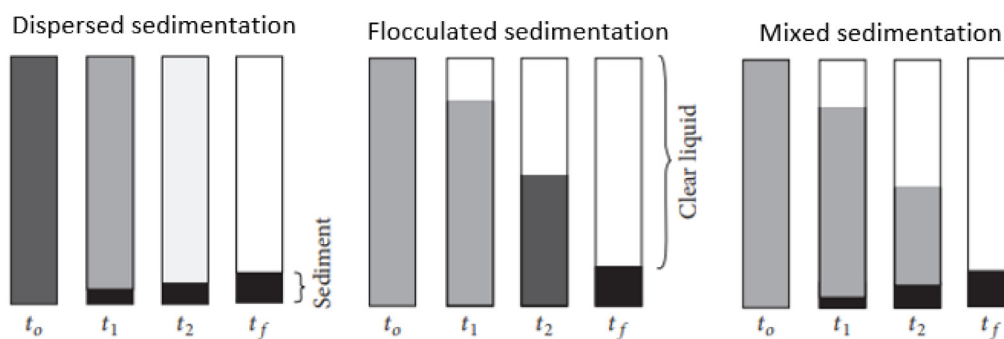


Fig. 19. Sedimentation types where t represents time and $t_0 < t_1 < t_2 < t_f$ (Ilyas et al., 2021).

glass bottle, and a camera takes photos of the vial at equal intervals. Hence, the sediment form is observed. To analyse NF stability, The obtained images are compared. The characterised NF is stable if the part size and dispersion remain constant (i.e., no sedimentation occurs). In all unstable NFs, tree behaviour can be observed. Fig. 19 shows the three behaviours of sedimentation, namely, (1) dispersed sedimentation with the gradual increase in sediment height from the bottom, as clarified by the solution, (2) flocculated sedimentation with time reduction in the sediment height and (3) mixed sedimentation with simultaneous occurrence of two previous phenomena in a NF (Tiara et al., 2017).

6.3. UV-visible spectral analysis method

Several researchers have used spectral analysis of UV–V to assess the stability of NFs. The stability of NFs is determined by monitoring the absorption characteristics, which corresponds to the fluid's particle concentration over time. Jiang's first proposed method in 2003 can only be used if wavelength absorption between 190 nm and 1100 nm is present in the scattered NPs (Chamsa-ard et al., 2017). In general, the NPs in the NF cohabit a linear relationship between the absorption intensity and concentration. In such a process, the variation of sedimentation time at supernatant particle concentration can be assessed using a UV–Vis spectral analyser, which measures NF absorbance. The major advantage of this method is that the NF analysis can produce a quantitative concentration.

6.4. Electron microscopy method

Determining the NF stability by measuring the particle size distribution using transmission electron microscopy (TEM) or scanning electron microscopy (SEM) devices. The digital image, known as the electron micrograph, can be captured with these microscopes, which offer a resolution of approximately 0.1 nm (Kong et al., 2017). A sedimentation mechanism is likely to occur in clusters of NPs which are discovered within the obtained images (i.e., NF is considered unstable) in total evaporation of the base fluid called the NPs aggregate. Hence, only low-particle concentration NFs are suitable for the TEM characterisation approach. NF is placed on a tape applied to the specimen holder, placed in a vacuum oven, and then dried in an oven without using heat. The SEM vacuum chamber is used to capture the particle images in the finished sample, then placed in the sample drying chamber. Fig. 20(a) and (b) show the SEM and TEM images of CuO NPs.

6.5. Light scattering techniques

The light scattering techniques are widely used to characterise dispersions. Particle attractions affect the stability of the NF. Measuring the variation of particle size and particle size distribution

can also be used to monitor particle aggregation. The SEM or TEM does not provide a true representation of the conformation of particles in fluids, thus should not be used to examine NPs after being dried (Shima et al., 2015).

The scattered laser light is collected in the process known as DLS. Due to Brownian motion, the random thermal motion of particles in a liquid and the speed of the movement depending on the particle size, liquid particles in suspension show thermal Brownian motion. Inert matter, which is less dense, moves faster and more dense matter moves slower. Based on the intensity variations of the scattered laser light, DLS measures the hydrodynamic diameter of particles. Conversely, DLS measures particle size over a larger sample volume.

7. Application of NFs in FPSC

In recent years, an increase in consideration of renewable energy resources in all countries because of the shortage of energy resources is observed. One renewable energy source that has come into prominence is the solar thermal energy systems for homes and industrials applications. Flat-plate collectors have been operating for over 30 years with little change in the designs or operating principles. FPSC has some advantages: being reliable, durable and inexpensive, but have some disadvantages such as low sensitivity and low efficiency at low irradiance and ambient temperature. The FPSC is effectively used for industrial and domestic applications and absorbs sunlight and converts it into thermal, passing through a clear working fluid such as oil, water and EG (Zayed et al., 2019). The disadvantages of FPSCs are the low convective heat transfer coefficients and low thermal efficiencies between working fluid and absorber. Therefore, enhancing the efficiency of solar collectors has become one of the current development areas. Working fluid is a critical feature that affects the thermal performance of flat plate collectors. One of the methods of increasing the efficiency of solar collectors is to use NPs in solar collectors. With the advancement in material technology, the possibility of high-performance NF has been realised. Fig. 21 shows the thermal efficiency enhancement of the FPSC having nanoparticles compared to the base fluid. In this literature, nanomaterials in solar liquid optimise the FPSC's thermal efficiency (Akram et al., 2020; Huang and Marefati, 2020; Liu et al., 2020). Moreover, key parameters such as size and kind of NP, mass flow rate, particle concentration and collector area can influence the thermal efficiencies of FPSC.

Experimental and theoretical studies on using NFs in FPSCs

Moghadam et al. (2014) examined FPSC efficiency and performance using NF CuO–H₂O. The area considered for absorption was 1.51 m². The experiment's average particle size was 40 nm, while the NPs volume fraction remained 0.4%. NF mass flow rate varied between 1 kg/min and 3 kg/min. The efficiency was increased by increasing the mass flow rate from 1 kg/min to 2 kg/min and

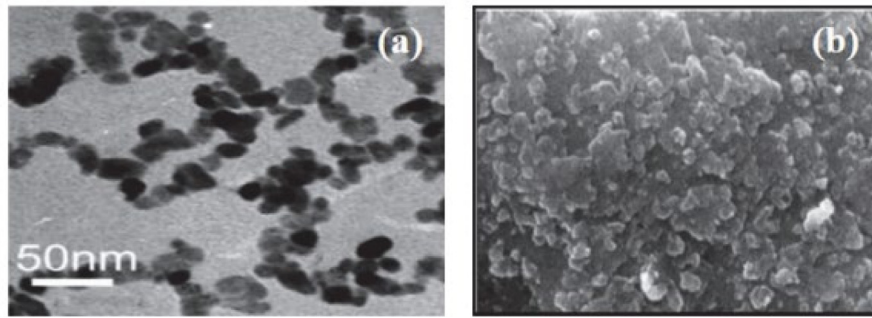


Fig. 20. CuO NPs micrograph. (a) TEM (Nallusamy, 2016) and (b) SEM (Razi and Saeedinia, 2011)).
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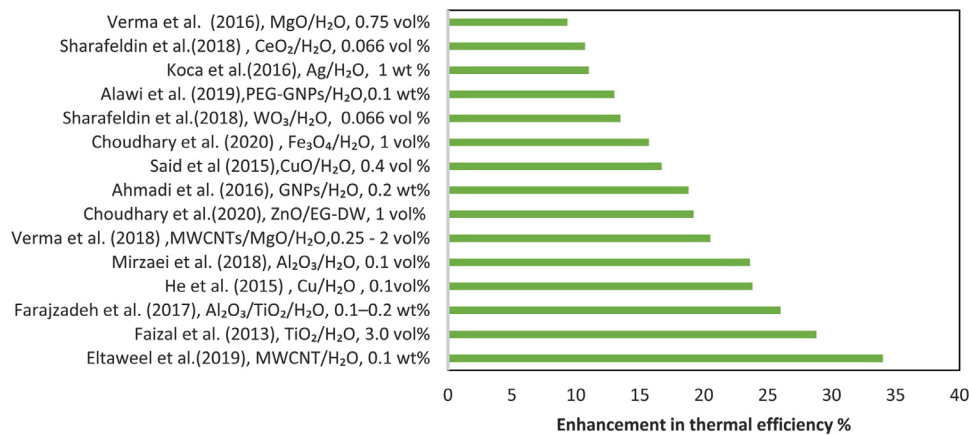


Fig. 21. Thermal efficiency enhancement of nanofluids in FPSC compared to base fluid.

decrease when the flow rate is further increased to 3 kg/min. A total of 2192, 2682 and 3248 Reynolds with a mass flow rate of 1 kg/min, 2 kg/min and 3 kg/min, respectively, were utilised. Results show that NF CuO/H₂O increases the efficiency of the collector by 16.7% compared with water.

Said et al. (2015) investigated FPSC performance enhancement analysis by Titanium Dioxide NF and PolyEG (PEG400) dispersant. For the collection system, the entire energy and energy analyses via TiO₂ were conducted. Figs. 22 and 23 show the complete experimental structure and diagram. The volume fractions used were 0.1% and 0.3%. A mass flow rate of 0.5 kg/min to 1.5 kg/min were considered. Improvement of the thermal conductivity of 6% with FV = 0.3% TiO₂ was observed. The viscosity decreased with the temperature increment and increased with the NPs loading. The energy efficiency increased as the volume fraction, and mass flow rate increased. As the volume fraction was reduced or mass flow was increased, energy efficiency decreased. The energy efficiency increased by 76.6% to 0.1% and 0.5 kg/min and was increased by 16.9% to 0.1% and 0.5 kg/min compared with water to the highest level of exergy efficiency.

Vakili et al. (2016) carried out graphene nanoplatelets NF applied in a volumetric solar collector for household hot water applications. The experiment was performed for the 35 °C–40 °C range for four different NFs, including one base fluid. For different weight fractions of 0.0005, 0.001 and 0.005, and different weight fluxes of 0.0075 kg/s, 0.015 kg/s and 0.225 kg/s, the experiment took place. The efficiency increased from 0.0075 kg/s to 0.0015 kg/s with the increase in weight flow rate but disappeared when the weight flow rate continued to increase from 0.015 kg/s to 0.225 kg/s because of the higher loss at the border. Mass flow rates of 0.0015 kg/s for NF and basic fluid were the highest collector efficiency. The efficiency was initially increased as the

weight fraction increased, but the efficiency was reduced because of the increase in weight fraction.

Michael and Iniyar (2015) experimentally studied the effect of NF (CuO/H₂O) on the efficiency of (2.08 to 1.05 m²) FPSC, as shown in Fig. 24. SDBS was used as a surfactant, and a forced and free convection experiment was carried out. Solar performance has been tested at a volume fraction of 0.05%; CuO/H₂O NF produces the highest temperature of 91.4 °C in the thermosyphon circulations and CuO/H₂O NF produces the highest temp. at 0.05 kg/s at 66.5 °C. For low volumetric fraction, higher collector efficiency improvement was observed when thermosyphon was used than forced convection. For NF CuO/water, the maximum efficiency was 57.98% in 0.1 kg/s. In thermosyphon, the maximum efficiency increase was 6.3%. Given the stability problem, NF performance was preferred with a low volume fraction compared to a high-volume fraction.

Shojaeizadeh et al. (2015) examined the Al₂O₃/water NF-based FPSC's energetic efficiency. The effect of different parameters such as the mass flow rate (m), the volume concentration of NPs (C), collector plate size (Ac), solar radiation (GT), collector inlet temperature (Ti) and ambient temperature (Ta). The area considered for absorption was 1.51 m². Sodium dodecyl benzene-sulfonate (SDBS) was a surfactant used for stability. The used volume fractions of the NF were 0.090696%, 0.094583%, 0.10293%, 0.11057%, 0.117686%, 0.1244%, 0.13082, 0.137%, 0.1423% and 0.1244%. With solar radiation, the exergy efficiency increased and was higher at low volume concentration.

Wang et al. (2020) numerically investigated effects of Cu, Fe₂O₃ and Al₂O₃ nanofluids on thermosyphon entropy generation. They found that nanofluids could enhance the thermal performance of thermosyphon, moreover, a reduction in overall entropy generation was obtained to be 41%, 32% and 29% for Cu, Fe₂O₃ and Al₂O₃, respectively.

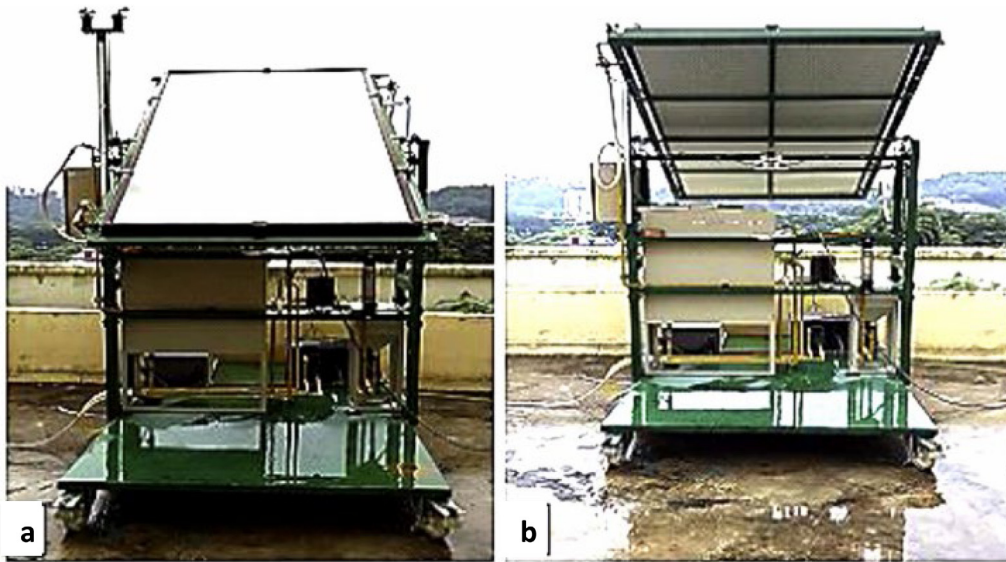


Fig. 22. Experimental setup photographs (a) Front part (b) Back part (Said et al., 2015).
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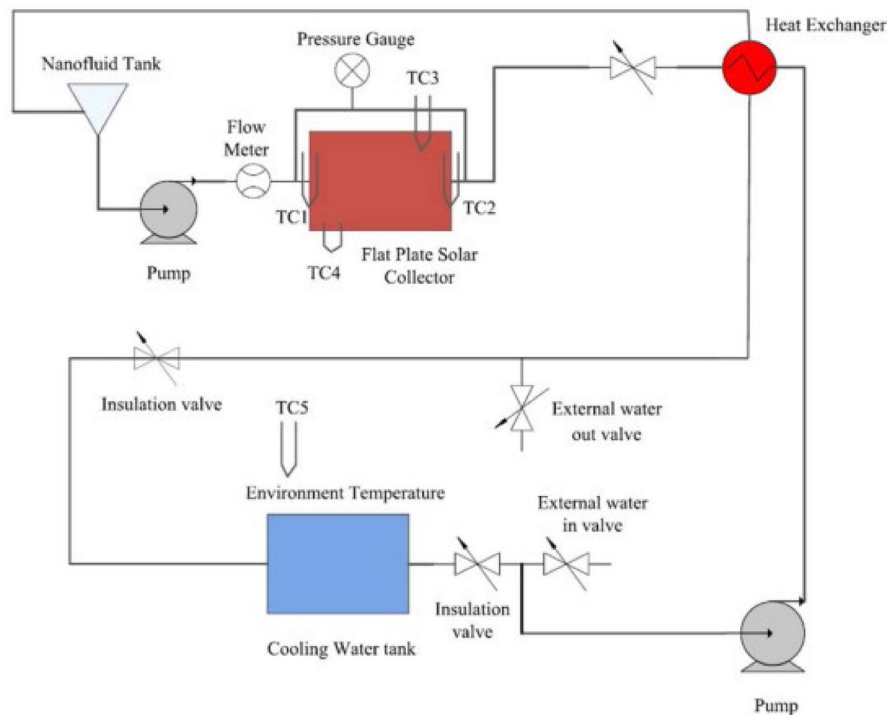


Fig. 23. Schematic of the final experimental setup (Said et al., 2015).
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Nasrin and Alim (2015) studied FPSC's thermal performance as a NF in forced convection with Cu/water . A rectangular section with dimensions 1 m to 0.15 m was an absorber plate (Fig. 25). The spherical shape of the NPs was 5 nm. For nondimensional governing equations along with boundary conditions, the Galerkin finite element method was used. The computational domain was discretised using the six-node triangular element. The effects on mean bulk temperature, medium subdomain velocity and dimensional exit temperatures, Nusselt numbers and collector efficiency were observed in the solar irradiance (I) and dimensional diameter (D). The I value are 200 W/m^2 , 215 W/m^2 , 230 W/m^2 and 250 W/m^2 and D are considered as 0.01 m,

0.012 m, 0.013 m and 0.015 m. With increasing I and decreasing D , the heat transfer rate increased, thus collector efficiency was further increased.

Yousefi et al. (2012) examined the impact on the efficiency of FPSC using $\text{Al}_2\text{O}_3/\text{H}_2\text{O}$ NF. A total of 1.51 m^2 absorption area and NP diameter of 15 nm were used. Testing with and without the surfactant Triton X-100 took place. The weight fractions considered for NPs were 0.2% and 0.4%, whereas the mass flow rate of 1 L/min to 3 L/min was different. The efficiency of NFs compared with water was increased. The solar collector efficiency with NFs of 0.2 wt% is 28.3% greater than water. The surfactant addition was shown to positively impact solar collectors' performance

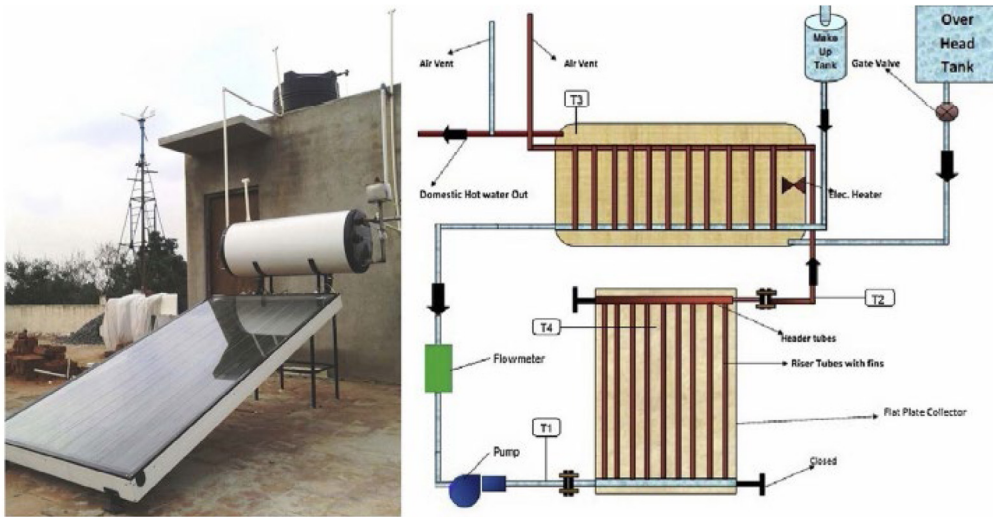


Fig. 24. Schematic of the final experimental setup (Michael and Iniyar, 2015).
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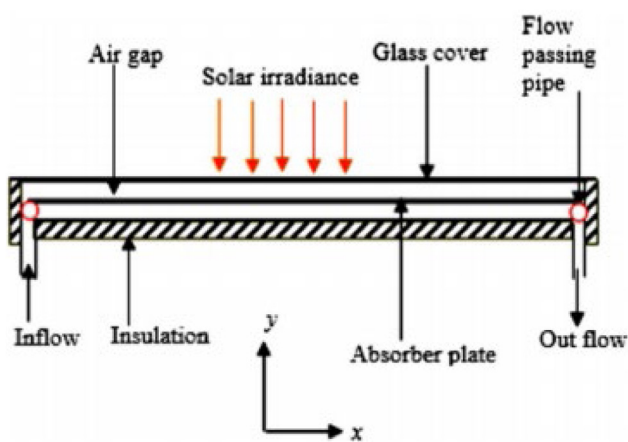


Fig. 25. Schematic of FPSC (Nasrin and Alim, 2015).

with increased maximum efficiency of 15.63% using a surfactant. The FPSC efficiency for low temperature ($T_i - T_a$) decreased with a rise in mass flow rates because the difference $FR(\alpha)$ decreased at low temperatures with the mass flow increment. Fig. 26 shows the experimental setup and schematic used for this study.

Mahian et al. (2014) studied the entropy generation and heat transfer in FPSC due to Al_2O_3 /water as a working fluid. Mass flow rate varied from 0.1 kg/s to 0.8 kg/s; volume concentration varied up to 4%, and particle size was 25 nm, 50 nm, 75 nm and 100 nm. The effect of various parameters on the Nusselt number, Bejan number, outlet temperature, entropy generation, heat transfer coefficient, particle size and various thermophysical properties and tube roughness were studied. Nusselt number was declining with increased volume fraction and size of NPs. As the NP volume increases, entropy generation decreases, and the temperature of the outlet increases. When solar radiation and ambient temperature decrease, the significance of roughness was increased.

Yang and Liu (2012) studied a thermosyphon open loop using NPs from CuO. The base fluid was water, and the mass concentrations of the NPs ranged from 0.1% to 1.5 wt%. The flow of boiling heat transfer in an evaporator improves by adding NPs. Furthermore, an optimum value was found for the concentration

(1 wt%). Results obtained for the effect of heat transfer coefficient improvement concentration are shown in Fig. 27.

Ekramian et al. (2014) studied the thermal performance of three different NFs composed of MWCNT, Al_2O_3 and CuO with mass percentages of 1%, 2% and 3%, respectively) used in a FPSC. To study the NP mass percent, mass flow rate, impact of inlet temperature on heat transfer coefficients and thermal efficiency, the influence of these three variables on both pure water and NFs was examined. Fig. 28 shows that CuO–water NF was more efficient than other NFs.

Roy et al. (2015) examined the solar flat plate collector's silver/water NF heat transfer characteristics (Figs. 29 and 30). The solar radiation ranged from 800 W/m² to 1000 W/m² and the volume concentration ranged from 0.01% to 0.03% and 0.04%. The influence on the collector efficiency and the convective heat transfer coefficient was studied by the mass flow rate of NF, the radiation heater flux, inlet temperature and volume concentration. With the increasing particle concentration and flow rates, the efficiency of the flat plate collector increases. For 0.04% of volume concentrations at 6 l/min, the system's maximum efficiency was estimated to be around 70%.

Hawwash et al. (2018) used water and alumina fluids in the concentrations of 0.1–3% for FPSC. A computer simulation was performed with a single-phase with temperature-dependent properties in an ANSYS/FLUENT study. The thermal efficiency of FPSC was most optimal when a concentration of 0.5% exists. Adding NPs with volumes above 0.5% does not enhance the solar collector's efficiency due to NPs' agglomeration.

Moravej et al. (2020) examined the results of a study using the asymmetric square absorbers of TiO_2 /H₂O NF instead of H₂O as circulating fluids. Increases in solar irradiance or flow rates are influenced thermal performance. The highest increase in efficiency was about 78% with 1 wt% TiO_2 /H₂O, representing the highest and average efficiency gains of 9.80% and 6.64% compared with H₂O. In addition, efficiency rates of 1 wt%, 3 wt% and by 5 wt% were improved by 17.41%, 27.09% and 33.54%, respectively.

Bazdidi-Tehrani et al. (2018) developed a 3D numerical model of a ribbed absorber using TiO_2 – H₂O and CuO–H₂O NFs. An increase in the volume percentage of NPs moderately improved the solar collector's efficiency. The ribbed absorber in comparison with the plain duct shows a rise of around 10%. The CuO–H₂O sample provided more energy efficiency than the TiO_2 –H₂O sample compared with the NFs tested (Fig. 31). Therefore, the

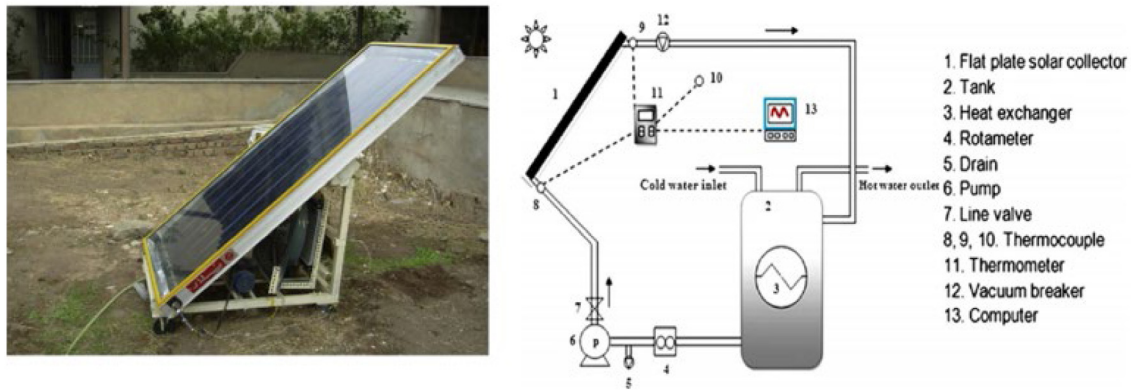


Fig. 26. Schematic of the final experimental setup (Yousefi et al., 2012).
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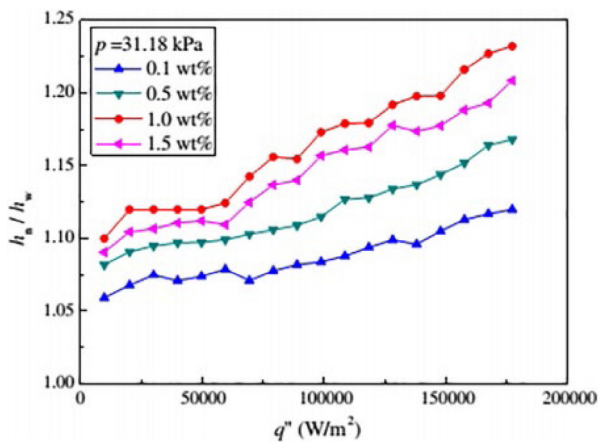


Fig. 27. Effect of concentration on the enhancement of heat transfer coefficients (Yang and Liu, 2012).
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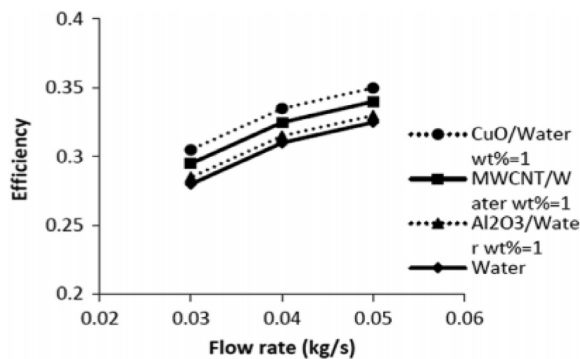


Fig. 28. Comparison of various NF thermal efficiencies at various mass flow rates (Ekramian et al., 2014).

performance achieved the highest value by 2.04% Vol-CuO/H₂O NF at 89%.

He et al. (2014) studied the FPSC by NFs. The Cu/H₂O NF in the sizes of 25 nm and 0.1 wt% are shown in the percentage increase efficiency up to 23.83% (Fig. 32). The 0.2 Wt%-Cu/H₂O was less efficient than 0.1 Wt%-Cu/H₂O because the NP concentration cannot be too much. In addition, Cu NP size received a significant impact on the absorber's energy efficiency.

Salavati Meibodi et al. (2015) investigated the effect of using SiO₂-EG/water NF to operate in a 1.59 m² FPSC, as shown in

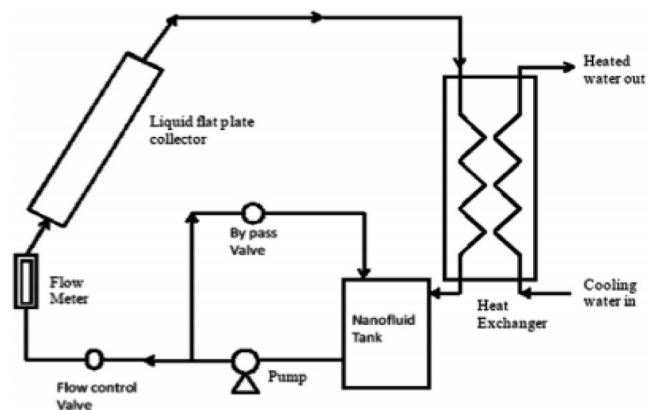


Fig. 29. Schematic of SWHS components (Roy et al., 2015).



Fig. 30. Experimental setup photograph (Roy et al., 2015).

Fig. 33. NPs have an average size of 40 nm with concentrations of 0.5%, 0.75% and 1%, a ratio of EG to water of 1:1 and flow rates of 0.018 kg/s, 0.032 kg/s and 0.045 kg/s. The NFs were stable because no sedimentation was seen after two weeks since preparation. Even though the thermal conductivity of SiO₂ is low, results indicate that using 1% SiO₂-EG/water NF yields an 8% increase in thermal efficiency (Fig. 34). The lower concentration also helped to lower the cost and increase the stability. The test results have

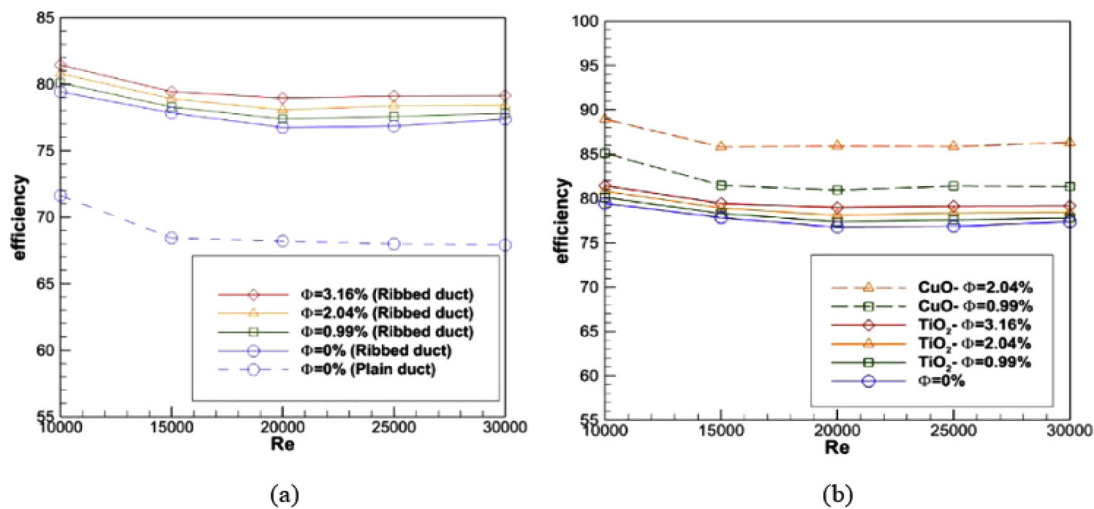


Fig. 31. Efficiency of (a) plain ducts and ribbed (b) TiO₂-water and CuO-water NFs (Bazdidi-Tehrani et al., 2018). Source: Permission from Elsevier; 5190450820221.

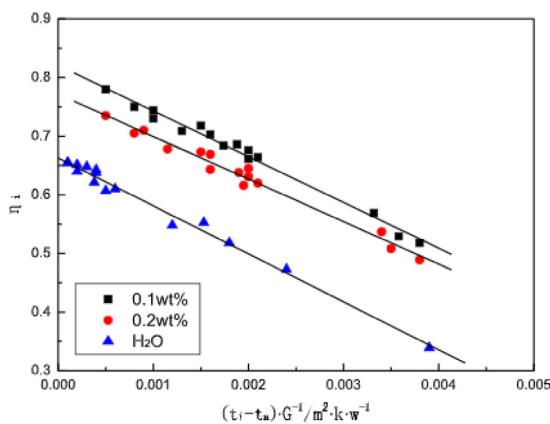


Fig. 32. Efficiency of FPSC with Cu- H₂O NFs (0.1 wt% and 0.2 wt%) and water as heat transfer fluids (He et al., 2014). Source: Permission from Elsevier; 5190451034927.

shown that the use of SiO₂ NF can increase the FPSC efficiency. Although the research concluded that the FPSC's performance increased more than that of using carbon nanostructure-based NFs with lower volume fractions, the FPSC's performance did not increase as much as when carbon nanostructure-based NFs are used with higher volume fractions.

Akram et al. (2019) examined the FPSC's thermal efficiency. The one-pot technique was used to functionally covalently GNP. Zeta potential is reflected in the stability of NFs for 45 days and no sediments. This experimental work has been performed with three mass flow rates of 0.0133, 0.0200 and 0.0260 kg s⁻¹, and three-volume 0.025%, 0.075% and 0.1%. At 0.1% mass and 0.00260 kg s⁻¹, the FPSC's maximum heat efficiency was 78% higher than the base fluid, as shown in Fig. 35.

Mirzaei et al. (2018) investigated the effect on thermal effectiveness of 1.51 m² FPSC by Al₂O₃- (20 nm 0.1 vol%) NF at different fluid rates of 1 L min⁻¹, 2 L min⁻¹ and 4 L min⁻¹. For this study, ASHRAE standards 86-93 have been considered. The study examined the optimal working condition of Al₂O₃-water and the standard operating fluid. Results show that the addition of NPs in the basic fluid has improved FPSC's thermal efficiency. Thermal efficiency increased as the flow rate rises with the maximum efficiency at the optimal flow rate. The optimal flow rate was 2

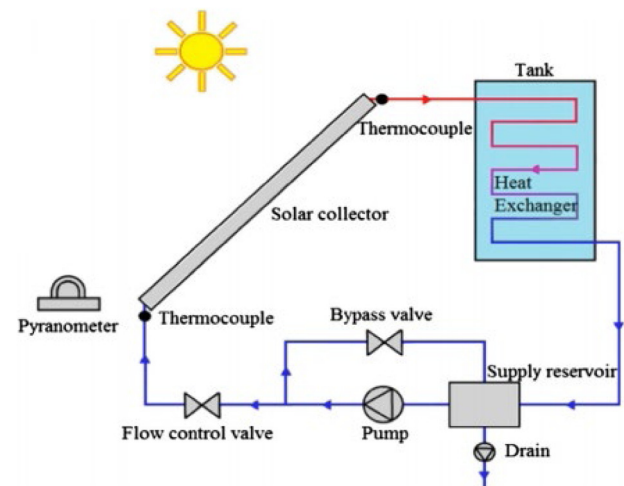


Fig. 33. Schematic of the experimental setup (Salavati Meibodi et al., 2015). Source: Permission from Elsevier; 5190440920886.

L min⁻¹, which is 23.6% of Al₂O₃-water NF compared with the water data, as shown in Fig. 36.

Verma et al. (2017) used various NFs such as TiO₂-H₂O, CuO-H₂O, MWCNT-water, SiO₂-H₂O and Al₂O₃-H₂O for experimental investigation on a 0.375 m² FPSC. Fig. 37 presents the methodology used for this study. In compliance with ASHRAE 93-2003, standard NF effects were calculated on entropy generation, exergy efficiency, thermal efficiency of FPSC and Bejan number. For the study, 0.25%, 0.50%, 0.75%, 1.0% and 1.5% volume fractions and 0.01–0.05 s⁻¹ mass flow rates and Triton X-100 surfactant were used. Testing has shown that the exergy efficiency of MWCNT/water nano-fluid has increased by 29.32% at volume 0.75% and the flow rate 0.025 kg s⁻¹, while the efficiencies of Graphene/H₂O, CuO/H₂O, Al₂O₃/H₂O, TiO₂/H₂O, SiO₂/H₂O and SiO₂/H₂O have increased by 21.46%, 16.67%, 6.97% and 5.74%, respectively, as represented in Fig. 25. For MWCNTs, a maximum decline of 65.55% in entropy generation was observed, followed by 57.89%, 48.32%, 36.84%, 24.49% and 10.04%, as previously mentioned for other NFs. The thermal efficiency of FPSC in the MWCNT/water, graphene/H₂O, CuO/H₂O, Al₂O₃/H₂O, TiO₂/H₂O and SiO₂/H₂O have improved by 23.47%, 16.97%, 8.28% and 5.09%, respectively.

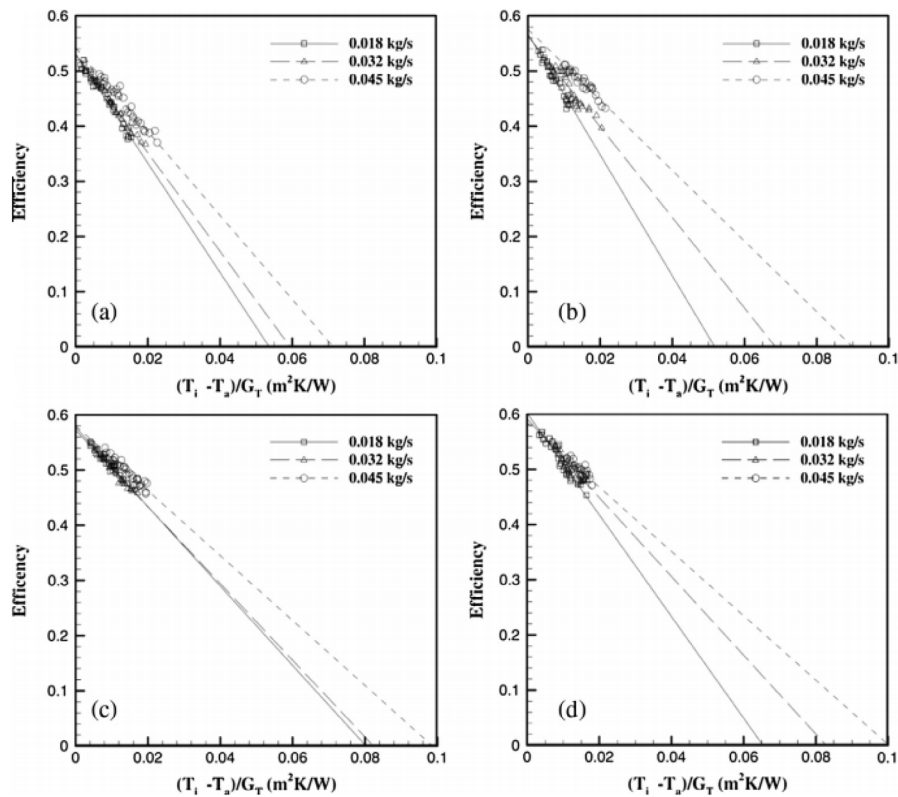


Fig. 34. Efficiency of the solar collector at different flow rates and concentrations: (a) 0%, (b) 0.5%, (c) 0.75% and (d) 1% (Salavati Meibodi et al., 2015). Source: Permission from Elsevier; 5190441041553.

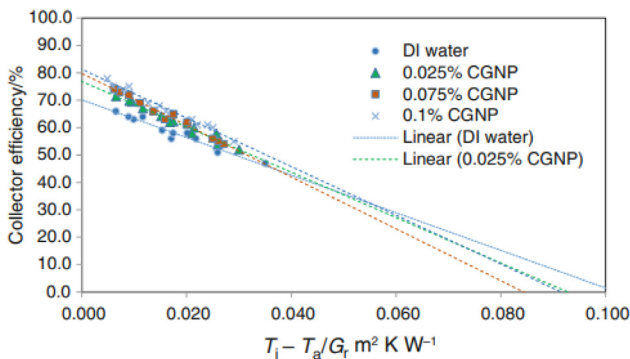


Fig. 35. Efficiency of FPSC at 0.0260 kg/s (Akram et al., 2019).

Farajzadeh et al. (2018) investigated the thermal performance of FPSC (1.85 m²) with the same concentration ratio of the Al_2O_3 water (20 nm at 0.1%) and TiO_2 -water (15 nm at 0.1%). The NFs were prepared using CTAB as a surfactant by a two-step method. The experimental and numerical investigation software was used for ASHRAE standard 93 and open-source computational fluid dynamics (CFD). Different flow volume rates at 1.5 L min⁻¹, 2.0 L min⁻¹ and 2.5 L min⁻¹ were considered. Based on the experimental results, a 0.1 mass% increase of Al_2O_3 -water, TiO_2 -water and 0.1 mass% of its mixture were observed in the thermal efficiency compared with 21% and 26% (water). Compared with the individual NF, the mixture thermal efficiency was increased, as shown in Fig. 38. The thermal efficiency was further enhanced with the mixture concentration from 0.1% to 0.2% mass. As NPs from TiO_2 are more expensive than Al_2O_3 , their mixtures are more economical and efficient.

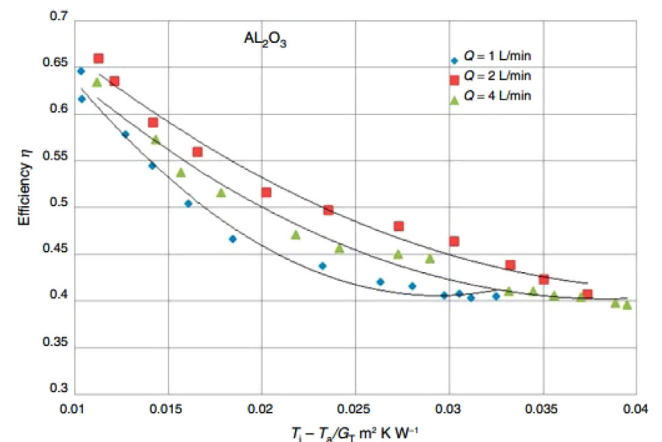


Fig. 36. FPSC efficiency at different flow rates (Mirzaei et al., 2018). Source: Permission from Elsevier; 5190450132074.

Moghadam et al. (2017) studied the 3D Al_2O_3 /water NF in flat plate solar collector by ANSYS Fluent at 30 inclination angles. The NF was Al_2O_3 /water with different concentrations of 0%–4% and particulate matter diameter 25–100 nm. With the Reynolds number increase, the coefficient of heat transfer from convection to conduction increased, the Richardson number increased, and the increase in the Richardson number and the particle volume fraction decreased. Results show that when NF is introduced, the heat transfer coefficient increased from 45% to 58%. The simulation also showed that entropy is generated quickly as the number of Reynolds increases and as the number of Richardson and the concentration of increased NF decrease. When a particle size of 25 nm increased the Richardson count, the pressure drop

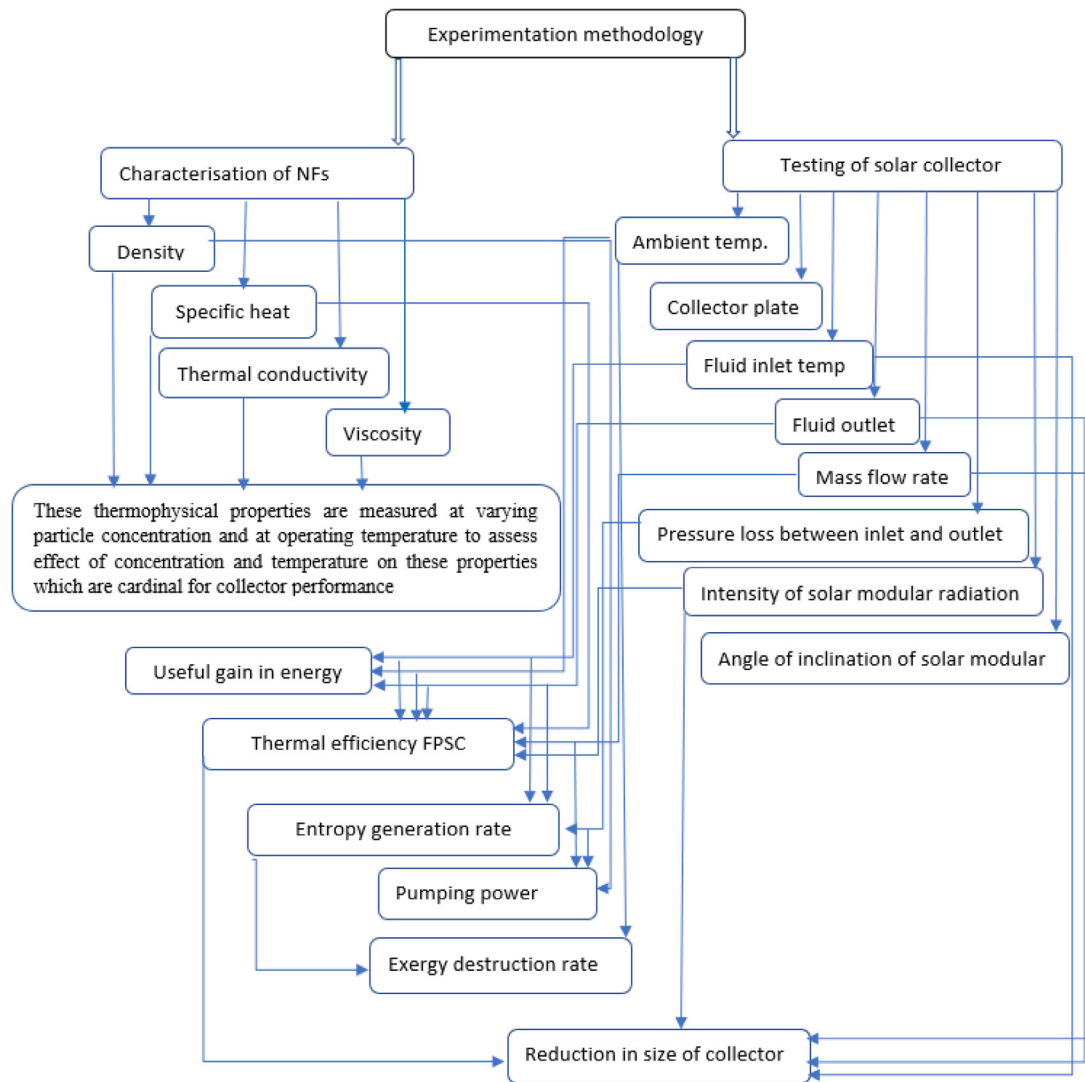


Fig. 37. Experimental methodology of FPSC (Verma et al., 2017).
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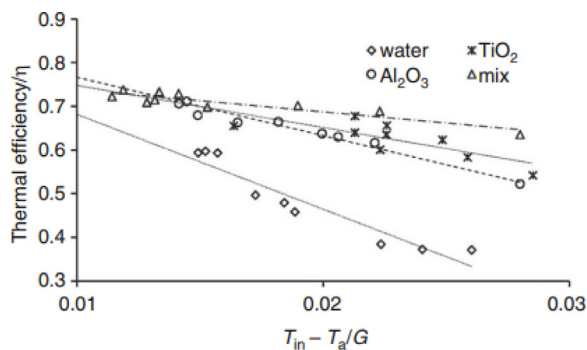


Fig. 38. Efficiency of FPSC with NFs (Farajzadeh et al., 2018).
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was significant. Although the Richardson number was considered constant, the pressure decrease value was reduced. The efficiency of FPSC in this study improved by 2% compared with the previous literature.

Karanth et al. (2011) used the fluent programmes and discrete transfer radiation model (DTRM) to model heat transfer and solar

radiation in FPSC. The panel comprises several parallel channels where the absorber plate is cooled at a one-through water mass flow rate. Fig. 39 shows a 3D computer domain which was used to conduct numerical simulations, showing that the absorber plate and the tube's temperature profiles have similar linear trends with simulated flow velocities (Fig. 40).

Table 6 illustrates a literature summary of previous investigations on FPSC by NFs.

8. Limitations and difficulties

The researchers continued the feasibility study of NFs and solar collectors in various applications for increased efficiency. Many complicated concerns can be pointed in various NF studies considering properties and their application in solar collectors. These are namely:

1. **Stability of NFs:** Long-term stability is the major and important requirement of NFs. Better NF stability results in better thermal conductivity. NFs have very strong van der Waals forces that tend to aggregate, thus preparing homogeneous suspensions is difficult; consequently, maintaining homogeneity in solutions is difficult. The better dispersion and stability of NFs constitutes one of the key requirements of solar thermal systems (Hussein, 2016).

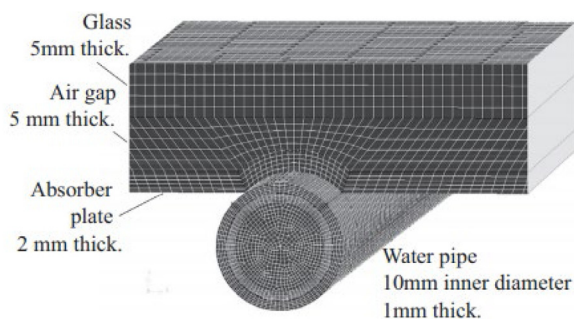
Table 6
Summary of previous studies on FPSC using NFs.

References	Type of investigation	Base fluid type	NPs			Collector area (m ²)	Observations
			Type	Volume fractions (%)	Size (nm)		
Noghrehabadi et al. (2016)	Experimental	water	SiO ₂	1	12	1	The solar collector efficiency increases with the increased as the mass flow rate increased.
Verma et al. (2016)	Experimental	water	MgO	0.25, 0.5, 0.75, 1.00, 1.25 and 1.5	40	0.375 m	The efficiency of the solar collector enhanced by 9.34% at 0.75% Vol and 1.5 l/min. It enhanced exetegetic efficiency by 32.23% and loss of pumping power by 6.84%.
Said et al. (2015)	Experimental	DI water	Al ₂ O ₃	0.1	13, 20	1.84	The highest energy efficiency was 73.7% in NPs 13 nm size, with a volume fraction of 0.1% and a mass flow rate of 1.5 kg/min, compared with 20 nm is about 70.7%.
Faizal et al. (2013)	Experimental	water	CuO, SiO ₂ , TiO ₂ and Al ₂ O ₃	3		2	Various reduction in size NPs is possible. Compared with the traditional fluids, the solar collector area can be reduced by 22.1%, 21.5%, 21.6% and 22.0% for CuO, SiO ₂ , TiO ₂ and Al ₂ O ₃ , respectively.
Vakili et al. (2016)	Experimental	Deionised water	Graphene	0.05, 0. 1 and 0. 5	Dia. = 2 μm, Thickness = 2 nm,	0.36	Initially, the collector efficiency improved with an increase in mass flow rate, but later decreased with increased mass flow rate, giving maximum efficiency at $\dot{m} = 0.015$.
Bioucas et al. (2018)	Experimental	Water +EG (70:30)	Graphene	0.05, 0.08 and 0.10	6–8		The maximum performance of FPSC is about 5.90%, with a volume fraction of 0.10 wt%. Performance can be increased using higher, flow-compatible and pumping conditions nanographene concentrations.
Genc et al. (2018)	Numerical	Water	Al ₂ O ₃	1, 2 and 3			The unit's performance increase in nanomaterial existence is about 5.5%–9.5%
Eltaweel and Abdel-Rehim (2019)	Experimental	Water	MWCNT	0.01, 0.05 and 0.1,	10–40 nm		Thermal efficiency of collector are about 16%, 21% and 34.13% With 0.01 wt%, 0.05 wt%, 0.1 wt% and highest exergy at 23.35%.
Choudhary et al. (2020)	Experimental	EG-DW	ZnO	0.2, 0.6 and 1	35 nm		Thermal effecting of FPSC with 1 vol% is about 19.2%, and energy parameter decreased by 62.5%.
Tong et al. (2020)	Experimental	Water	Al ₂ O ₃ , CuO, Fe ₃ O ₄ , MWCNT	Al ₂ O ₃ : 1.0 vol%, CuO: 0.5 vol%, Fe ₃ O ₄ : 0.005 vol%, MWCNT: 0.0015 vol%	Al ₂ O ₃ : 20, 50, and 100 nm, CuO: 40 and 80 nm Fe ₃ O ₄ : 15 and 30 nm MWCNT: 20, 50, and 80 nm		Thermal efficiency of FPSC at Al ₂ O ₃ : 3.8%, CuO: 4%, Fe ₃ O ₄ : 3%, MWCNT: 8.8%. Selecting nanomaterial MWCNT results in higher performance.
Yousefi et al. (2012)	Experimental	H ₂ O	Al ₂ O ₃	0.2–0.4	15	1.51	Using Triton X-100, the average efficiency improved by 15.63%
Mirzaei et al. (2018)	Experimental	H ₂ O	Al ₂ O ₃	0.1	20	1.51	The efficiency of collectors has increased by about 23.6%.
Arikan et al. (2018)	Experimental	H ₂ O/EG	Al ₂ O ₃ , ZnO	0.25	68.12 mm and 0.196 mm	170 (L) 90 (W) 0.5 (T)	The maximum efficiency increase was 15.13%.
Kashyap et al. (2018)	Experimental	EG: H ₂ O	ZnO	0.02	50	1550 mm and 345 mm	With a grooved tube, peak efficiency was achieved at 5.95%.

(continued on next page)

Table 6 (continued).

References	Type of investigation	Base fluid type	NPs			Collector area (m ²)	Observations
			Type	Volume fractions (%)	Size (nm)		
Dehaj and Mohiabadi (2019)	Experimental	H ₂ O	MgO	0.014–0.032	74.5	4	The maximum efficiency of the collector with flow rate 0.014 and 0.032 vol% at 14 L/min was 69% and 77%.
Saffarian et al. (2020)	Numerical	H ₂ O	Al ₂ O ₃ , CuO	1 and 4		1.425	Heat transfer enhanced by 78.25% using wavy pipe and CuO–H ₂ O.
Munuswamy et al. (2020)	Experimental and Numerical	H ₂ O	Al ₂ O ₃ , CuO	0.2–0.4	20–50	0.5	By using Al ₂ O ₃ NF in the finned tube, efficiency has been improved by 4%. The use of CuO–H ₂ O shows an incremental improvement of 3%.
Jouybari et al. (2019)	Experimental and theoretical	H ₂ O	SiO ₂	0.4–0.6	20–30	0.63	FRUL of 0.6% and 0.4% decreased by and 51.7%, and 55.2%, respectively.
Tomy et al. (2016)	Numerical	H ₂ O	Ag	0.1, 0.3 and 0.4 vol%			The difference between the numerical and the test data was lower than $\pm 2\%$.
Koca et al. (2017)	Numerical	H ₂ O	Ag	0–1	15	304 mm 220 mm	With 1 wt % NF, efficacy increased to 11%.
Bazdidi-Tehrani et al. (2018)	Numerical	H ₂ O	TiO ₂	0.2 and 0.4 vol%	27	Plate width = 20 cm	When NF and ribbed duct were used, efficiency increased by 10%
Sadeghzadeh et al. (2019)	Numerical	H ₂ O	TiO ₂	0–0.3	20	0.5, 0.2 and 0.001	The MLP-ANN model provided the best prediction for thermal performance.
Farajzadeh et al. (2018)	Experimental	H ₂ O	Al ₂ O ₃ /TiO ₂	0.1–0.2 wt%	20/15	2 m and 0.925 m	The thermal efficiency was improved to 26%.
Okonkwo et al. (2020)	Experimental and theoretical	H ₂ O	Al ₂ O ₃ /Fe, Al ₂ O ₃	0.05–0.2 vol%	29/46	1.51 m	The efficiency of Al ₂ O ₃ is greater than Al ₂ O ₃ /Fe hybrid

**Fig. 39.** Mesh for the FPSC (Karanth et al., 2011).

2. Behaviour of surfactant usage: One type of blockage is to use a suitable surfactant to prepare NFs for solar collectors. Many studies showed that surfactants have enhanced dispersion in working NFs and minimised particle agglomeration. This study examined the use of different surfactants in various solar collectors to improve suspension and NF stability criteria and see if they opposed damages (Awais et al., 2021). Various types of NF surfactants were reported to influence the NF stability and solar thermal adsorption characteristics. Choi et al. (2018) tested MWCNTs/water NFs' stability and solar thermal adsorption qualities by adding different surfactant types (SDBS, CTAB, SDS and TX-100). To summarise their research, dispersion stability and absorption properties are strongly influenced by these surfactants used to make NFs. DBS showed the optimum performance among four surfactants and was also recommended for use with DASC and other thermal receptors.

3. NP size and volume concentration: All solar energy systems focus on NP size and mass concentrations regardless of type. Kasaieian et al. (2015) studied more research on the NPs' impact in solar systems.

4. Viscosity of NFs: NF viscosity increases according to an increasing NF volume and decreases at the same shear rate in solar energy at an increased temperature. Said et al. (2013) studies on FPSC viscosity of Al₂O₃/water and Al₂O₃/water-ethylene NFs are highly affected by temperature, volume concentrations and base fluid. Increasing NP mass fractions and water-based NFs increase viscosity as non-Newtonian fluid at a higher temperature. Thus, NFs of water-EG show the behaviour of Mahian et al. (2013). For example, a higher viscosity increase was found in one of the best solar absorbing fluids as carbon nanotube-based NFs, although the weight of NPs was very small. Therefore, the solar thermal collector needs higher pump power. Increasing the pump capacity to achieve the desired heat efficiency is not preferred since the system increases the operating costs (Said et al., 2021).

5. Pumping power and pressure drop: Using of a higher viscosity NF than the base fluid results in pressure drop increment. Therefore, an increase in the pumping power is required. Duangthongsuk and Wongwises (2010) noticed that an increase in the volume fraction of TiO₂/water NF with pressure drop under turbulent flows increases in their tests.

6. Cost of NFs: Higher production of NF suspensions is a major threat in the use of NFs in solar collectors due to difficult processes. NFs are generally produced by either one or two-step methods. However, sophisticated apparatus is necessary to produce NFs using these methods (Wole-oshio et al., 2020). NF costs for solar thermal systems such as heat exchangers. Solar collectors are stressed to reduce their application as a disadvantage.

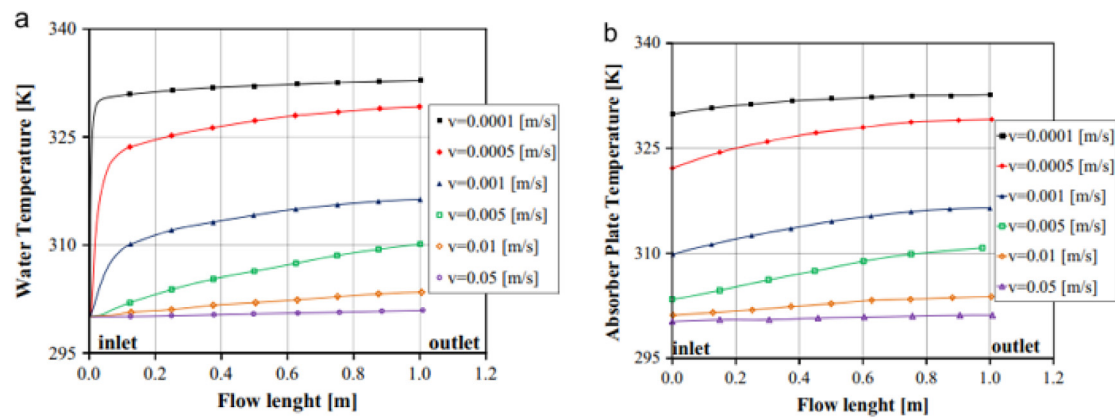


Fig. 40. (a) Water temperature at a different flow rate (b) Absorber plate at a different flow rate (Karanth et al., 2011).

7. Erosion and corrosion of NFs: The work liquid NPs can cause erosion and corrosion on the surface of thermal equipment for long-lasting use. Bubbico et al. (2015) examined TiO_2 , Al_2O_3 , SiC and ZrO_2 NFs on the metal surface, erosion and corrosion susceptibility. Results showed that NPs are causing surface damages from chemical corrosion and near negligible mechanical erosion.

9. Conclusions and future recommendations

The present study provides a comprehensive overview and analysis of the recent development related to solar technology, namely FPSC with nanotechnology (i.e., NFs) in this type of collector. Among the more solar fluids, NFs are advanced working fluids made by NPs colloidal dispersion in base fluids for solar collectors. The NFs are used as heat transfer mediums in FPSC due to their ability to increase the thermal performance of collectors, thus both residential and industrial uses may be applied effectively. Some key conclusions are summarised below from this study:

1. Suitable NPs' dispersion and long-term stability are necessary to absorb the sun and increase solar collector efficiency properly.
2. At increased volume fractions, the collector efficiency is enhanced, but as the volume fraction high increases, the efficiency decreases due to decreasing heat transfer rate and increasing viscous forces.
3. Improved collector efficiency can be attributed to the addition of the surfactant to the NF, suitable selection of pH and effective particle size.
4. The main reason for improving the collector efficiency was that the thermal conductivity of NFs was unnaturally increased.
5. Performative improvements were achieved with carbon nanomaterials, MWCNTs and SWCNTs, compared with metals and metallic oxides-based NFs for energy efficiency of the absorber.
6. Pumping power is increased unfavourably due to the high viscosity of NFs.
7. Experiments can be carried out with a higher concentration of NF.
8. A different type of NF is tried every time to achieve new results, especially when adding surfactant.
9. A varying pH value can be used to examine the effect of the pH on NF performance.
10. Preparation of NF is another alternative in repeatable experiments. Transformer oil and EG base solar fluids are appropriate for this task, and their effects can be measured.
11. Further effort is needed to investigate the environmental and economic reliabilities using NFs in solar collectors.

12. Further research needs to focus on different important nanotechnological challenges and their application in the solar collector, such as long-term stability of NFs, Brownian motion of particles, corrosion of NFs, pumping power, pressure drop NPs agglomeration, changing thermophysical properties and high cost.
13. The impacts of NP sedimentation on the efficiency of FPSC need further study.
14. Further investigations are required to study the hybrid NF's effect on the performance of PSCs.
15. Examination on the FPSC's performance with PCM for heat storage when NFs are used as heat transfer fluids.
16. Analysis of the FPSC's performance when the NFs are used as solar fluids with built-in nanocoating on the glass cover of FPSC.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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