

# The recent progress of nanofluids and the state-of-art thermal devices

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**Abstract.** Nanofluids have been continuously investigated as innovative fluids in the last decades. The unique thermophysical properties exhibited by nanofluids have led to a variety of applications in modern energy-scarce environments. The purpose of this paper is to provide an overview of recent advances in nanofluids in cooling as well as to summarize the controversies of the existing applications. The development of electronic devices has heightened the need for an effective cooling system. Nanofluids in solar collector applications have greatly improved the thermal efficiency and solar energy utilization compared to conventional fluids, which can greatly alleviate today's energy problems. The cost of nanofluids in commercial applications may be too high, and long-term stability cannot be guaranteed due to the impacts of the thermal efficiency of nanofluids. More innovative approaches are needed to improve the cost and stability of nanofluids to cater to the commercial market. These results aim to provide a deeper understanding of the thermophysical properties and applications of nanofluids and to understand the limitations and potential for future improvements.

**Keywords:** nanofluids, thermal properties, Solar thermal collectors, CPU cooling.

## 1. Introduction

Since the 1990s, the renewal and iteration of technologies such as atomic force microscope (AFM) and scanning tunneling microscope (STM) for nanosystems have promoted the continuous development of the microfluidic field [1]. Thereinto, the one of the most remarkable cases is the nanofluidics, which studies the fluid movement under nano-confinement [2].

Some nanofluids formed at appropriate nanoparticle concentrations can exhibit unique thermal and electrical properties. This has greatly changed scholars' understanding of traditional fluid heat transfer and brought new research fields and development directions. The earliest origin of this is Maxwell's research on the relationship between ion dispersion and thermal conductivity more than a century ago, but under the technical conditions at that time, the stability of metal micro atoms became the biggest stumbling block [3]. Choi first reported in 1995 that thermal conductivity can still be more than 10% higher than that of conventional fluids with a small volume ratio of nanoparticles. [4]. Routbort et al. in 2008 could save approximately 1 trillion Btu of energy by using nanofluids to replace cooling and heating water in industrial production. For the U.S. electric industry, the energy savings from using nanofluids could power about 50,000-150,000 homes for a year [5]. Donzelli et al. showed that a special class of nanofluids can act as smart materials for controlling the flow of heat. Nanofluids can rapidly switch between states with poor thermal conductivity and states with good heat dissipation [6]. CPU cooling, solar thermal collector, and chip fabrication are also mainstream applications of nanofluidics today.

The reason why nanofluids have unprecedented thermal conductivity is that the size of nanoparticles is 1000 times smaller than that of micro atoms, which is more conducive to the diffusion of particles [3]. According to the current research, nanofluids are divided into mixed Nanofluids and traditional nanofluids [7]. Generally the one-step chemical method, one-step physical method, and two-step method are used to prepare nanofluids, of which the most commonly used is the two-step method [8]. Density, specific heat capacity, thermal conductivity, viscosity, and particle radius are some of the main factors affecting the thermal properties of nanofluids. In the classical Maxwell

equation, the volume fraction is an important factor affecting thermal conductivity. However, in fact, the radius of particles is also a factor that cannot be ignored. Afterwards, the relationship between generalized thermal conductivity and particle size is proposed. The motivation of this paper is to summarize the latest developments in nanofluids and their thermal performance applications (mainly around CPU cooling and solar collectors). It will also briefly summarize the problems that still exist in the state-of-art nanofluids approaches and provide an outlook on future developments.

## 2. Basic descriptions

In engineering, it is unavoidable to consider the heat transfer efficiency of heat exchangers. A common method to maximize the performance of heat exchangers is to include working fluid in the machine. So far, water is extensively used to increase the efficiency of heat equipment due to water's availability. For instance, Microsoft has delivered their data center into the sea to provide a reliable environment to cool computers. However, water cooling has low efficiency. Alternatively, nanofluids, which is basically a mixture of nanoparticles and a base fluid, can be used due to their remarkable advantages in thermal conductivity. There are two major approaches for preparing nanofluids, which are one step method and the two-step method. In a one-step process, the preparation of nanoparticles and dispersion in a base fluid is handled spontaneously which will produce high stability nanofluids. Nevertheless, the procedures require a high cost and the impurities are significant. The most commonly used technique is the two-step method in which nanoparticles are obtained and then added to base fluids. This production process can generate nanofluids in bulk, despite the low stability of nanofluids obtained. Hence methods of improving stability such as pH Adjustment and Magnetic Agitation should be engaged [9]. The heat capacity of nanofluids, defined as the capability of the nanofluid to absorb heat energy without any phase change [10], can be modified using several equations. For instance, Zhou et al. have suggested an equation for CuO-based fluid when base fluid and nanoparticles have a slight discrepancy in density. Consequently, the equation does not satisfy water-based Al<sub>2</sub>O<sub>3</sub> nanofluid [11]. As listed in Table.1, researchers have suggested several equations describing a variety of types of nanofluids' specific heat capacity. All the definitions of the variables (listed in tables, figures and equations) in the paper are summarized in Table. 2.

**Table 1.** Table for specific heat capacity of nanofluids

Type of nanofluid	Equation	Author name
CuO based	$C_{p,nf} = \frac{[(1 - \varphi)\rho_f C_{p,f} + \varphi\rho_{np} C_{p,np}]}{[\varphi_f \rho_f + (1 - \varphi)\rho_{np}]}$	Zhou et al. [11]
Al <sub>2</sub> O <sub>3</sub> based	$C_{p,nf} = \frac{\rho_{np}\varphi_{np} C_{p,np} + \rho_s\varphi_s C_{p,s} + \rho_{ns}\varphi_{ns} C_{p,ns}}{\rho_{np}\varphi_{np} + \rho_s\varphi_s + \rho_{ns}\varphi_{ns}}$	Shin et al. [9]

Another significant property of nanoparticles is their excellent thermal conductivity. The thermal conductivity of nanoparticles is influenced by their internal conditions such as size, shape, and concentration of nanoparticles. Meanwhile, it is affected by external environments such as temperature, pH, sonication time and frequency, magnetic field, and aggregation [10]. About a hundred years ago, Maxwell tried to formulate the conductivity of spherical particles in small concentrations using simple models (variables definition mentioned in Table. 2):

$$K_{nf,Maxwell} = K_f \frac{K_{np} + 2K_{bf} + 2\varphi(K_{np} - K_{bf})}{K_{np} + 2K_{bf} - 2\varphi(K_{np} - K_{bf})} \quad (1)$$

However, limitations existed for solid-liquid materials such as nanofluids. Later, people began to correct Maxwell's equation based on effective medium approximations and proposed several constants to address the issue of uncertainty. A famous version of correlation is proposed by Hamilton and Crosser [12], who included the constants n, modified by the sphericity of particles:

$$K_{nf,H\&C} = K_{bf} \frac{K_{np} + (n-1)K_{bf} + \varphi(n-1)(K_{np} - K_{bf})}{K_{np} + (n-1)K_{bf} - \varphi(K_{np} - K_{bf})} \quad (2)$$

**Table 2.** Definition for abbreviations.

Nomenclature	
$\varphi$	volume concentration of nanoparticle
$\rho$	density
$C$	heat capacity
$K$	Thermal conductivity
Subscripts	
$nf$	nanofluid
$bf$	base fluid
$np$	nanoparticle
$s$	salt eutectic
$ns$	nanostructure

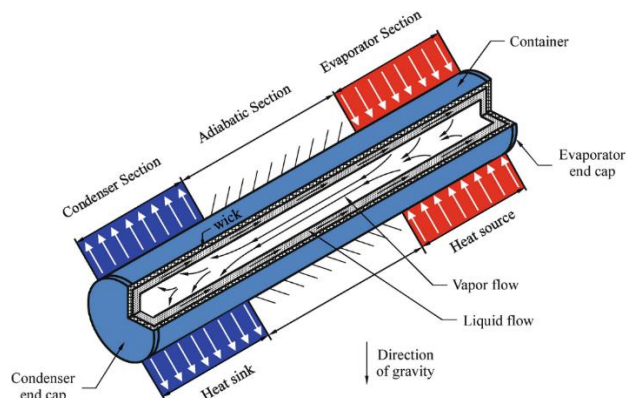
### 3. Nanofluids in CPU cooling

The increasing usage of electronic components demands a more efficient cooling system, rather than conventional poor performance methods of water and air cooling. To develop appropriate methods of cooling, it is crucial to ensure that the cooling fluid has good thermal conductivity and low viscosity since extra energy is required to pump the fluid when the viscosity is high. Heat transfer engines can be designed according to two technologies called passive cooling and active cooling. Passive cooling involves utilizing heat transfer phenomena such as conduction, convection, and radiation to transfer heat to surroundings. Examples of passive cooling include heat sinks, which is made up of thermal conducting metals with fin-like structure. The heat from the CPU is first transferred to the metal and finally dissipated into the air. This method is energy-free despite the fact that it requires more material when the CPU generates more heat. Another cooling system is called an active cooling system, the cooling liquid may be pumped to cool the CPU and then be cooled by fans. The cooled fluid is then pumped back to the cool CPU. Though electricity is required to drive the system to work, this technique is more efficient in heat transfer.



**Figure 1.** A sketch of heat sink [15].

Several researchers have designed microchannel-based convection, which is a kind of active cooling system for CPU cooling. In an experiment conducted by Al-Rashed et al., the researchers adapted a single-phase cooling system that pumped the cooling nanofluid to cool the CPU and then recollected the air-cooled fluid at the same phase as the original fluid. Based on ANSYS fluent stimulation for laminar flow, nanofluid (CuO in water at 2.25 vol.%) cooling gives a lower temperature value ranging 0.6 K compared with water cooling. Another nanofluid sample of concentration of CuO in water at 0.86 vol.% also exhibits advantages over water in heat transfer [13]. Balaji, T. et al. have conducted experiments using microchannel heat sinks, which is another type of microchannel-based convection technique, as illustrated in Figure 1. The results demonstrated that for functionalized graphene-based nanofluid, the heat transfer ability is better than water as the base fluid [14, 15].



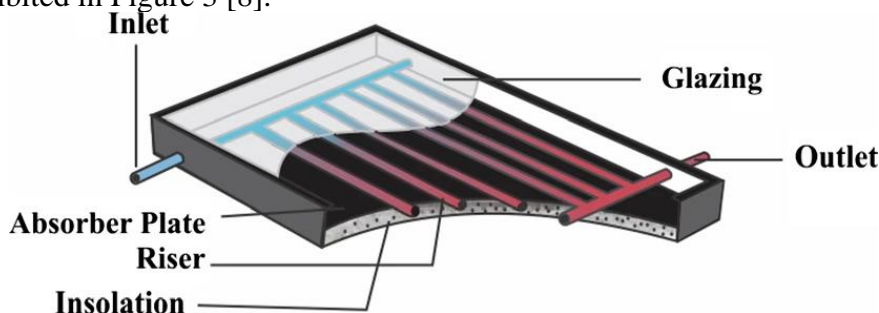
**Figure 2.** Graphic illustration of a thermosyphon heat pipe [16].

A heat pipe is a heat-transfer device that employs phase transition to transfer heat between two solid interfaces. Owing to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors. The most common type of heat pipe is the thermosyphon heat pipe, as illustrated in Figure 2 [16]. Mahdi R et al. have justified with experimental results that thermosyphon-based heat transfer equipment has significant merits over conventional copper heat exchangers [17]. Specifically, with the adoption of ethylene glycol-based nanofluids and water-based nanofluids in heat pipes, the enhancement of efficiency is 29.5% and 13.3% correspondingly compared with ethylene glycol and deionized water [18]. According to Yousefi et al., who have constructed a CPU-cooling heat pipe filled with nanofluids, 0.5 wt. %  $\text{Al}_2\text{O}_3$ /water nanofluid significantly minimizes thermal resistance by 22% [19].

#### 4. Nanofluids in Solar thermal collectors

The solar collector is a heat exchanger that converts solar radiation. The research of solar devices began in the 18th century. With the continuous development of scientific knowledge, equipment technology and working medium, the efficiency of solar devices is constantly improving.

Since the 21st century, with the continuous advancement of research in the field of nanofluids, this efficient heat transfer medium has been used in solar collectors. At present, it can be divided into non-concentrated collectors and concentrated collectors [20]. The main difference between non-concentrated STC and concentrated STC is the ratio difference between the collector and absorption zone. The ratio of collector surface area to absorber area of non-concentrated STC is 1. The ratio of collector area to absorber area of concentrated STC is greater than 1 [21]. More reflective devices are used in concentrated STC to concentrate solar radiation. The working fluid temperature of concentrated STC is much higher than that of non-concentrated STC [22]. A sketch of a solar thermal collector is exhibited in Figure 3 [8].



**Figure 3.** Graphic illustration of a solar thermal collector [8].

The intermolecular attraction in working fluid nanofluids will lead to agglomeration. It will increase the size and density of nanoparticles, and the viscosity will also increase, thus affecting the stability of the nanofluid [23], and therefore cannot be used as a working fluid. Nevertheless, human research later found that adding a Surfactant to the nanofluid solves this problem [24]. By changing the nanofluid's transport properties to improve the fluid's stability, the problem of instability of the

nanofluid during the operation was solved, and this method was later applied in production. Later, it was soon found that the addition of Surfactant had some negative effects on production use, and scientists needed to develop more methods to improve stability without negative effects [8].

The thermal conductivity of nanofluid increases with increasing fluid concentration. The working performance of nanofluids in solar collectors was found to be related to the volume fraction and particle size of the nanofluid by Mahian et al. [25]. In the last decade, alumina nanofluids and copper nanofluids have been extensively studied as working fluids in solar collectors. The superiority of the thermal performance of alumina nanofluids compared to conventional fluids was demonstrated by Yousefi et al. [26]. Teng et al. found by measurement that the smaller the particles within the nanofluid, the higher the temperature and the higher the thermal conductivity [27]. Parvin et al. in 2014 showed that the solid volume fraction, Reynolds number, and flow rate of copper nanoparticles are all important influences on the entropy generated by copper-water nanofluids [8].

Hybrid nanofluids were also an important research direction in the previous decade to improve the thermal efficiency of collectors by mixing to obtain the synergistic properties of their constituent elements. Suresh et al. in 2011 extracted nanofluids from powders of alumina and copper oxide by hydrogen reduction technique and the viscosity of alumina-copper nanofluids increased more significantly with the increase in concentration [28]. Sarkar et al. demonstrated better thermal conductivity of hybrid nanofluids in 2015 [29]. Shojaeizadeh et al. first reported in 2015 that reducing the flow rate and flow inlet temperature of alumina-water nanofluid in flat plate collector applications can lead to an increase in energy kinetic efficiency [30]. Multi-walled carbon nanotubes (MWCNTs) with single-walled carbon nanotubes in nanofluid applications significantly improved the energy efficiency. Said et al. 2015 tested the use of SWCNTs-water nanofluid as working fluid and showed a huge improvement in energy efficiency and efficiency compared to water. The efficiency sensitivity was strongly influenced by the operating conditions, and the nanofluid clearly showed high efficiency when the operating facility sensitivity of the tested nanofluid was lower than that of the tested water [31]. Deng et al. also designed a new flat-plate solar collector with an array of microchannel heat pipes that can reach a maximum instantaneous efficiency of 80 [32].

Later graphene oxide nanofluid, cerium dioxide nanofluid, and titanium dioxide were also investigated as new collector working fluids. Graphene oxide nanofluid with a volume concentration of 0.012% showed great potential as a collector working fluid [33]. Water and cerium dioxide/water nanofluids were calculated for efficiency based on ASHRAE criteria and the results were 21.5% higher compared to water [34]. Surfactant-free rutile titanium dioxide/water nanofluid also showed a significant increase in efficiency compared to conventional fluids [35].

## 5. Future outlook

The commercial applications of nanofluidic devices are still limited since the production of nanofluids may not be cost-effective. The stability of nanofluid in the long run, which is the most obvious obstacle, remains unsolved. Strict procedures for maintenance are required for a nanofluidic cooling system since the thermal properties of nanofluids are influenced by several factors (e.g., temperature and pH). Another issue related to nanofluids is uncertainty during the production of nanofluids. For instance, the sedimentation of nanoparticles is hard to control, which may lead to an increase in the viscosity of the final nanofluid. Consequently, the experimental results of different investigators vary depending on the experimental conditions. When the viscosity of nanofluid generated increases, extra electricity is required to pump the nanofluid into the cooling system.

In future research, a different combination of base fluids and nanoparticles may be explored to find the best nanofluid for a cooling system. To make nanofluids for commercial usage, it is essential to cut costs. Innovations are also required to improve the manufacturing process of nanofluids to produce stable nanofluids. For example, the two-step methods have the capability to produce nanofluids in bulk for a low cost, if the stability of nanofluids produced can be enhanced, nanofluids can meet market demand.

## 6. Conclusions

In summary, this paper discusses nanofluids from the perspective of thermophysical properties. The unique thermophysical properties of nanofluids have led to a wide range of applications in contemporary resource-poor era. Nowadays, with the increasing usage of electronic components, the application of nanofluids has greatly increased the cooling efficiency and user-friendliness of electronic components. The application of nanofluids in solar collectors is also particularly impressive, greatly increasing the thermal efficiency of using solar energy and helping to alleviate energy problems. Nevertheless, the economic efficiency and long-term stability of nanofluids in commercial applications still need to be improved. Changing the combination of nanoparticles and base fluids is a research direction to solve this problem to cater to the market, by addressing this issue to industrialize the application of nanofluids in the daily life of human beings. These results offer a guideline for new developments and applications of nanofluids in the 21st century, which will help future researchers to investigate more applications of nanofluids in thermophysical properties.

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