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ADVANCEMENTS IN SOLAR DESALINATION: A COMPREHENSIVE REVIEW ON THE APPLICATION OF HYBRID NANOFLUIDS IN SOLAR STILLS

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ABSTRACT

This comprehensive review paper investigates recent advancements in the field of solar desalination, with a specific focus on the innovative application of hybrid nanofluids in solar stills. The paper provides a detailed analysis of the synthesis methods employed for hybrid nanoparticles, emphasizing the significance of both physical and chemical synthesis techniques. Notably, the review underscores the cost-effectiveness and ease of use associated with chemical synthesis methods. The synthesis and production processes of hybrid nanofluids are explored in depth, highlighting key considerations in achieving optimal thermophysical properties. The review identifies critical factors influencing the stability of hybrid nanofluids, with a particular emphasis on the role of particle surface charge. Various procedures ensuring the stability of hybrid nanofluids are discussed, providing valuable insights for researchers and practitioners in the field. Furthermore, the paper offers a comprehensive overview of the integration of hybrid nanofluids in solar stills, showcasing their potential to enhance the efficiency of solar desalination systems. The findings presented in this review contribute to a deeper understanding of the synergistic effects between nanofluids and solar still technology, paving the way for further advancements in sustainable and efficient water desalination processes.

Index Terms- Nanoparticles, Nanofluid stability, Nanofluid synthesis, Solar still, Nanofluid-based solar still.

INTRODUCTION

Securing access to clean drinking water is an essential requirement for all life on Earth. However, the availability of safe drinking water on the planet's surface is decreasing daily, with over 2000 million people residing in water-stressed regions facing the challenge of inadequate access. Independent estimates suggest that the world is on a trajectory to experience a substantial 40% global water shortage by 2030. Given the escalating water scarcity, there is an urgent need to explore viable solutions to meet the increasing demand for clean water for all living organisms. [1]

However, the effectiveness of solar still is hindered by the challenge of lower productivity. As a result, researchers have undertaken the development of efficient solar still designs and integrated various methods to enhance performance. Diverse approaches to improve solar still performance include the utilization of hollow and solid fins with different geometries, incorporation of sensible and latent heat storage materials, integration of dyes, exploration of different wick materials, and the implementation of forced condensation. These efforts aim to overcome the productivity constraints of solar still, making it a more efficient and reliable solution for addressing the critical issue of water scarcity. [2]

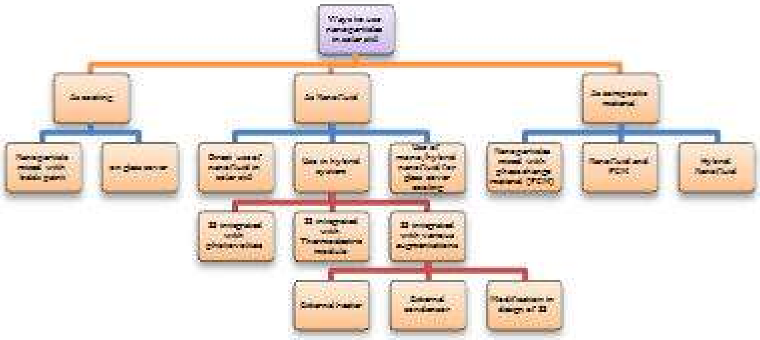

Figure 1

Different applications of nanofluids/nanoparticles in solar still [2]
Various methodologies exist for incorporating nanoparticles and nanofluids into solar stills, presenting innovative approaches to enhance their performance. The integration of these nanomaterials introduces novel possibilities for improving efficiency and addressing the productivity challenges associated with traditional solar still designs. One avenue involves the incorporation of nanoparticles into the structure of hollow and solid fins, each exhibiting distinct geometries. This strategy aims to leverage the unique properties of nanoparticles to enhance heat transfer and, consequently, increase the overall productivity of the solar still.Another approach involves the integration of nanofluids as sensible and latent heat storage materials within the solar still system. Nanofluids, composed of nanoparticles dispersed in a base fluid, offer improved thermal properties, enabling more efficient heat absorption and retention. This enhances the overall performance of the solar still by optimizing the energy transfer process.[3]

Basics of Nanofluid

Nanofluids represent a class of advanced heat transfer fluids engineered by dispersing nanometer-sized particles, typically metallic or non-metallic, into a base fluid, such as water or oil. These nanoparticles, often ranging from 1 to 100 nanometers in size, significantly alter the thermal and rheological properties of the base fluid, leading to enhanced heat transfer capabilities. The concept of nanofluids gained prominence due to their superior thermal conductivity compared to traditional heat transfer fluids, enabling improved efficiency in various thermal management applications. The dispersion of nanoparticles within the fluid matrix results in increased thermal conductivity, thereby enhancing the fluid's ability to conduct and transfer heat. Commonly studied nanomaterials include metallic oxides like alumina, copper oxide, and titanium dioxide. Researchers focus on understanding nanofluid stability, synthesis methods, and the impact of nanoparticle concentration on thermal properties. These nanofluids find applications in diverse fields, including electronics cooling, solar energy systems, and biomedical devices, due to their potential to optimize heat transfer processes. [2]

Nanofluids have garnered significant attention and found diverse applications across various industries owing to their remarkable thermal properties. One prominent application lies in the field of electronics, where nanofluids serve as effective cooling agents for electronic devices. The enhanced thermal conductivity of these fluids helps dissipate heat more efficiently, thereby mitigating the risk of overheating and improving the overall performance and reliability of electronic components. In the realm of renewable energy, nanofluids play a pivotal role in solar thermal systems. Their ability to absorb and transfer heat efficiently makes them valuable in solar collectors, contributing to increased energy conversion efficiency. [4]

I. Nanoparticles

Nanomaterials are characterized by having one or more external dimensions at the nanoscale or possessing internal or surface structures within this range. Nanostructured materials take the form of composites, wherein nano-objects are intricately embedded in a matrix, leading to the classification of such materials as nanocomposites. When a material consists of two or more discernible phases, and one of these phases exists at the nanoscale, the overall material is deemed nanostructured. In instances where nano-objects are uniformly dispersed within a continuous medium, it is termed a nanodispersion. These definitions underscore the diverse nature of nanomaterials, highlighting their unique structural characteristics and the various ways in which nanoscale features manifest within a material's composition. [28-29]

Nanofluids refer to colloidal suspensions of nanometer-sized particles or nanofibers within a liquid medium. These stable suspensions are composed of nanoparticles dispersed in diverse liquid solvents. Recognized for their effectiveness as heat transfer fluids, nanofluids enhance the thermophysical properties of conventional heat transfer fluids, making them valuable in applications where efficient heat transfer is crucial. [28-29]

Nanoparticle	Thermal Conductivity (W/mK)
Cu	401
CuO	76.5
MgO	6
Al	238
Al_2O_3	40
Fe	75
Fe_2O_3	6
TiO_2	8.4
Au	310
Ag	429
SiC	490

Table I Thermal conductivity of different Nanoparticles [30-36]

II. Methods of preparation of nanofluid

The initial stage in leveraging nanoparticles to augment the heat transfer characteristics of a conventional fluid involves the formulation of nanofluid. This process extends beyond mere amalgamation, necessitating specific prerequisites such as achieving a uniform, enduring, and stable suspension. Importantly, it mandates that there be no chemical alteration in the base fluid, and the occurrence of minimal nanoparticle agglomeration is imperative. [4] As per the principles of colloid chemistry, once a particle attains a critical size, it attains stability, preventing sedimentation.

Nanofluid synthesis can be accomplished through two distinct methods: (1) the single-step method and (2) the two-step method. [2]

- **Single-step method:** A single-step method in nanofluid synthesis involves the direct and simultaneous creation of nanofluid through a single process, typically without the need for multiple stages or intricate procedures.[5] This streamlined approach aims to simplify the synthesis of nanofluids, reducing complexity and potentially enhancing efficiency. The single-step method often entails the incorporation or synthesis of nanoparticles directly into the base fluid, allowing for a more straightforward and time-efficient production process. This method may involve techniques such as one-pot synthesis, where nanoparticles are formed and dispersed in the fluid in a unified step, offering a convenient and practical means of preparing nanofluids for various applications.[6-8]
- **Two-step method:** The two-step method in nanofluid synthesis involves a dual-stage process for creating nanofluids with specific characteristics. This method typically consists of two main steps: nanoparticle preparation or synthesis, followed by their dispersion or incorporation into a base fluid.
- **Nanoparticle Synthesis:** In the first step, nanoparticles are synthesized or prepared using various techniques such as chemical precipitation, sol-gel synthesis, or physical methods like laser ablation or vapor condensation.

This step aims to produce nanoparticles with desired size, shape, and material properties. The choice of the synthesis method depends on the characteristics required for the intended application. [12-14]

- **Dispersion in Base Fluid:** The second step involves dispersing the synthesized nanoparticles into a base fluid. This dispersion process is crucial for achieving a stable and well-dispersed nanofluid. Techniques like ultrasonication, stirring, or homogenization are commonly employed to prevent nanoparticle agglomeration and ensure a uniform distribution within the fluid. The choice of base fluid, such as water, oil, or ethylene glycol, depends on the application and the desired thermal properties of the nanofluid.The two-step method allows for a controlled and tailored approach to nanofluid synthesis. It provides flexibility in optimizing both the nanoparticle characteristics and their dispersion within the fluid, thereby influencing the overall thermal conductivity and heat transfer properties of the resulting nanofluid. This method has been widely employed in research and industrial applications to design nanofluids with enhanced performance for specific thermal management needs, including cooling systems and heat exchangers.[9-11]

III. Characterization of Nanofluid

- Nanofluids are a class of engineered fluids that incorporate nanometer-sized particles into a base fluid, often water or oil, to enhance their thermal and physical properties. The nanometer-sized particles, typically ranging from 1 to 100 nanometers, are dispersed uniformly in the base fluid, creating a stable colloidal suspension. This unique combination of nanoparticles and the base fluid leads to several distinctive characterizations of nanofluids, making them a subject of intense research and interest in various scientific and industrial applications. [15-16]
- One key characteristic of nanofluids is their enhanced thermal conductivity compared to traditional fluids. The addition of nanoparticles, such as metal oxides, carbon-based materials, or other nanomaterials, significantly improves the heat transfer capabilities of the fluid. This heightened thermal conductivity is attributed to the increased surface area and unique heat transfer mechanisms exhibited by the nanoscale particles, making nanofluids promising candidates for applications in advanced cooling systems, heat exchangers, and thermal management devices. [17-18]
- Moreover, nanofluids exhibit notable changes in their rheological properties. The addition of nanoparticles influences the viscosity and flow behavior of the fluid. While some nanofluids may display Newtonian behavior, others exhibit non-Newtonian behavior, such as shear-thinning or shear-thickening, depending on the concentration and type of nanoparticles. Understanding these rheological changes is crucial for designing and optimizing the performance of nanofluids in various engineering applications, such as in pumping systems and pipelines. [19-21]
- In addition to their thermal and rheological enhancements, nanofluids also often demonstrate improved stability and dispersion characteristics. Achieving a stable and well-dispersed nanofluid is essential for maintaining its desired properties over time. Various surfactants and stabilizing agents are employed to prevent particle agglomeration and settling, ensuring the long-term stability of the nanofluid. The stability of nanofluids is crucial for their successful implementation in practical applications, where consistent performance is required. [22-23]
- While nanofluids offer several advantages, challenges such as cost, potential toxicity of nanoparticles, and scalability issues must be addressed for widespread commercial use. Ongoing research continues to explore novel nanomaterials and formulation techniques to overcome these challenges and unlock the full potential of nanofluids in diverse fields ranging from electronics cooling to renewable energy systems. [24]

IV. Understanding the Mechanics of Heat Transfer Improvement in Nanofluids

- In this segment, we delve into the prospective mechanisms contributing to the improved heat transfer observed in nanofluids.

- **Brownian motion:** Brownian motion plays a crucial role in the behavior of nanoparticles in nanofluids. Brownian motion refers to the random and continuous motion of particles suspended in a fluid medium due to collisions with molecules of the surrounding fluid. In the context of nanofluids, where nanoparticles are dispersed in a base fluid, Brownian motion influences the stability, dispersion, and overall characteristics of the nanofluid. In nanofluids, Brownian motion is a dynamic force that counteracts gravitational settling and other aggregation mechanisms. The continuous motion of nanoparticles helps maintain their dispersion throughout the fluid, ensuring a uniform distribution. This is particularly important for applications where a stable and homogeneous nanofluid is essential, such as in heat transfer processes. Brownian motion also influences the effective thermal conductivity of nanofluids. The random movement of nanoparticles enhances their interaction with the surrounding fluid molecules, leading to improved thermal transport properties. As a result, nanofluids exhibit enhanced heat transfer characteristics compared to the base fluid alone. [2]

- **Liquid layering at liquid/particle interface:** The phenomenon of liquid layering at the liquid/particle interface refers to the arrangement of liquid molecules in distinct layers around nanoparticles suspended in a fluid. This layering effect is a consequence of the intermolecular forces and interactions between the liquid molecules and the nanoparticle surface. Understanding the liquid layering at this interface is crucial in the study of nanofluids and has implications for various applications, particularly in the context of colloidal and nanoscale systems. The liquid layering phenomenon has implications for the stability and dispersion of nanofluids. The layers of liquid molecules act as a barrier against particle aggregation or settling. This stabilization effect is particularly relevant in preventing the nanoparticles from agglomerating and maintaining a well-dispersed state within the fluid. It also has implications for the rheological and thermal properties of the nanofluid, influencing its overall behavior in various applications.Researchers often study the liquid layering phenomenon to gain insights into the intermolecular forces governing the behavior of nanofluids. This understanding aids in the development of strategies to control and manipulate the properties of nanofluids for specific applications, such as improving heat transfer efficiency in thermal systems or optimizing the performance of nanomaterial-based devices. [25-27]In summary, liquid layering at the liquid/particle interface is a critical aspect of nanofluid behavior, influencing stability, dispersion, and interactions between nanoparticles and the surrounding fluid. Researchers continue to explore the intricacies of this phenomenon to unlock its full potential for advanced applications in nanotechnology and materials science.

CONCLUSIONS

- In conclusion, the comprehensive review on the advancements in solar desalination, specifically focusing on the application of hybrid nanofluids in solar stills, highlights a promising avenue for addressing water scarcity challenges. The synthesis of hybrid nanofluids through both physical and chemical methods is explored, with a preference for the cost-effective chemical synthesis technique. The review emphasizes the critical role of stability in hybrid nanofluids, underlining the significance of particle surface charge for achieving and maintaining stability.

- The integration of hybrid nanofluids in solar stills presents a noteworthy stride towards enhancing the efficiency of solar desalination processes. The unique thermophysical properties of nanofluids, coupled with their stability, contribute to improved heat transfer and overall performance in solar still systems. This synthesis of nanotechnology and solar desalination holds promise for addressing global water scarcity issues, providing a sustainable and efficient solution.

- As we move forward, further research and development in this field are essential to optimize hybrid nanofluid formulations, tailor them to specific environmental conditions, and scale up their application in real-world solar desalination projects. The collaborative efforts between nanotechnology and renewable energy sources, as evidenced in the hybrid nanofluid-solar still integration, pave the way for innovative and eco-friendly solutions to meet the growing demand for fresh water resources across the globe.

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