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TECHNIQUES FOR THE ENHANCEMENT OF FREE OR NATURAL CONVECTION USING NANOFLUIDS: AN OVERVIEW

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ABSTRACT

As compared to the analytical or numerical work on the natural convection in nanofluids, very less experimental work has been reported in literature. Enhancement in thermal conductivity is conveyed in literature for all types of work. A high enhancement in heat transfer coefficient as compared to base fluid is reported in analytical and numerical investigation of the natural convection in nanofluids. While maximum experimental research work shown the degradation in the heat transfer coefficient as compared to base fluid. In this study, a comparative analysis is reported for the experimental work on the investigation of heat transfer phenomena in nanofluids.

I. Introduction

The necessity of high heat flow processes has created significant demand for new technologies to enhance heat transfer. For example, microprocessors have continually become smaller and more powerful, and as a result heat flow demands have steadily increased over time leading to new challenges in thermal management. Many methods are available to improve heat transfer in processes. The flow of heat in a process can be calculated based on:

$$Q = hA\Delta T$$

where Q is the heat flow, h is the heat transfer coefficient, A is the heat transfer area, and ΔT is the temperature difference that results in heat flow. A greater temperature difference ΔT can lead to increase the heat flow, but ΔT is often limited by process or material constraints. Maximizing the heat transfer area is a common strategy to improve heat transfer, and many heat exchangers such as radiators and plate-and-frame heat exchangers are designed to maximize the heat transfer area. However, this strategy cannot be employed in microprocessors and micro electromechanical systems (MEMS) because the area cannot be increased. In aerospace and automotive systems, increasing the heat transfer area can only be achieved by increasing the size of the heat exchanger which can lead to unwanted increases in weight. Heat transfer improvements can also be achieved by increasing the heat transfer coefficient h either by using more efficient heat transfer methods, or by improving the transport properties of the heat transfer material. Additives are often added to liquid coolants to improve specific properties. For example, glycols are added to water to depress its freezing point and to increase its boiling point. The heat transfer coefficient can be improved via the addition of solid particles to the liquid coolant (i.e. Microfluids, nanofluids).

Micrometer or millimeter sized solid particles added into a base liquid can improve the thermal conductivity of the fluid. Although such solid additives may improve the heat transfer coefficient of the liquids, particle application is limited because of the sedimentation of large particles, clogging flow channels, erosion of pipelines and causing a pressure drop [1]. A very small amount of nanoparticles, when dispersed uniformly and suspended stably in base fluids, can provide impressive improvements in the thermal properties of base fluids. Nanofluids, which are a colloidal mixture of nanoparticles (1– 100 nm) and a base liquid (nanoparticle fluid suspensions) is the term first coined by Choi in the year 1995 at the Argonne National Laboratory to describe the new class of nanotechnology based heat transfer fluids that exhibit thermal properties superior to those of their base fluids or conventional particle fluid suspensions [2]. Nanofluids can be used for a wide variety of industries, ranging from transportation to energy production and in electronics systems like microprocessors, Micro-Electro-Mechanical Systems (MEMS) and in the field of biotechnology. A nanofluid coolant could flow through tiny passages in MEMS to improve its efficiency. If nanofluids improve chiller efficiency by 1%, a saving of 320 billion kWh of electricity or an equivalent 5.5 million barrels of oil per year would be realized in the US alone. A nanofluid can also be used for increasing the dielectric strength and life of the transformer oil by dispersing nano diamond particles. Nanofluids can be used in following specific areas:

1) Heat-transfer nanofluids.
2) Tribological nanofluids.
3) Surfactant and coating nanofluids.
4) Chemical nanofluids.
5) Process/extraction nanofluids.
6) Environmental (pollution cleaning) nanofluids.
7) Bio- and pharmaceutical-nanofluids.
8) Medical nanofluids (drug delivery and functional tissue–cell interaction).

I. Synthesis of Nanofluids

Nanoparticles in general, and metal nanoparticles in particular, are investigated in the context of diverse research perspectives. Among these, catalysis, biology, drug delivery, materials science, photo-physics, and novel phenomena are most important. Each of these areas has a specific emphasis, although the synthetic methodologies have some overlap. The particles may have to be presented in different forms, and for that, specific modifications in the synthetic approach are necessary.

1.1 Two-step Method

Nanoparticles, nanofibers, nanotubes, or other nanomaterials used in this method are first produced as dry powders by chemical or physical methods. Then, the nanosized powder will be dispersed in a fluid in the second processing step with the help of intensive magnetic force agitation, ultrasonic agitation, high-shear mixing, homogenizing, and ball milling. Due to the high surface area and surface activity, nanoparticles have the tendency to aggregate. The important technique to enhance the stability of nanoparticles in fluids is the use of surfactants. However, the functionality of the surfactants under high temperature is also a big concern, especially for high temperature applications. Due to the difficulty in preparing stable nanofluids by two-step method, several advanced techniques are developed to produce nanofluids, including one-step method.

1.2 One-Step Method

To reduce the agglomeration of nanoparticles, a one-step physical vapor condensation method used to prepare Cu/ethylene glycol nanofluids [3]. The one-step process consists of simultaneously making and dispersing the particles in the fluid. In this method, the processes of drying, storage, transportation, and dispersion of nanoparticles are avoided, so the agglomeration of nanoparticles is minimized, and the stability of fluids is increased. The one-step processes can prepare uniformly dispersed nanoparticles, and the particles can be stably suspended in the base fluid. The vacuum-SANSS (submerged arc nanoparticle synthesis system) is another efficient method to prepare nanofluids using different dielectric liquids. The different morphologies are mainly influenced and determined by various thermal conductivity properties of the dielectric liquids. The nanoparticles prepared exhibit needle-like, polygonal, square, and circular morphological shapes. The method avoids the undesired particle aggregation fairly well. One-step physical method cannot synthesize nanofluids in large scale, and the cost is also high, so the one-step chemical method is developing rapidly. Another novel one-step chemical method used for preparing copper nanofluids by reducing $CuSO4 \cdot 5H2O$ with $NaH2PO2 \cdot H2O$ in ethylene glycol under microwave irradiation ([4]. Well-dispersed and stably suspended copper nanofluids were obtained. Stable ethanol-based nanofluids containing silver nanoparticles could be prepared by microwave assisted one-step method. In the method, polyvinylpyrrolidone (PVP) was employed as the stabilizer of colloidal silver and reducing agent for silver in solution.

1.3 Other Novel Methods

A continuous-flow microfluidic micro-reactor was developed to synthesize copper nanofluids [5]. By this method, copper nanofluids can be continuously synthesized, and their microstructure and properties can be varied by adjusting parameters such as reactant concentration, flow rate, and additive. CuO nanofluids with high solid volume fraction (up to 10% of vol) can be synthesized through a novel precursor transformation method with the help of ultrasonic and microwave irradiation. The precursor Cu(OH)2 is completely transformed to CuO nanoparticle in water under microwave irradiation. The ammonium citrate prevents the growth and aggregation of nanoparticles, resulting in a stable CuO aqueous nanofluid with higher thermal conductivity than those prepared by other dispersing methods. The aqueous organic phase-transfer method used for preparing gold, silver, and platinum nanoparticles on the basis of the decrease of the PVP's solubility in water with the temperature increase [6]. Phase-transfer method is also applied in preparing stable kerosene-based Fe3O4 nanofluids. Oleic acid is successfully grafted onto the surface of Fe_3O_4 nanoparticles by chemisorbed mode, which lets Fe_3O_4 nanoparticles have a good compatibility with kerosene [7].

II. RHEOLOGICAL PROPERTIES OF NANOFLUIDS

2.1 Thermal Conductivity

The thermal conductivity enhancement ratio is defined as the ratio of the thermal conductivity of the nanofluid to that of the base fluid and this ratio depends on the material, size and shape of the particle, volume concentration and the operating temperature itself. The influence of the type of material on the thermal conductivity enhancement has no effect of relatively low thermal conductive particles and positive enhancement with higher thermal conductivity particles. For instance, the enhancement of thermal conductivity using metal particles is higher that the metal oxide particles. However, it is difficult to create metal particle nanofluids without particles oxidizing during the production process. The smaller in particle size higher will be the enhancement. Since the surface to volume ratio will be higher for small diameter particles which results in uniform distribution of particles gives and the best enhancement. The most commonly used geometric shapes of the particles are spherical and cylindrical. The cylindrical particles show an increase in thermal conductivity enhancement due to a mesh formed by the elongated particles that conducts heat through the fluid. This indicates the elongated particles are superior to spherical for thermal conductivity. The thermal conductivity enhancement increases with increased particle volume concentration. Metal oxide particle volume concentrations below w= 4–5% produces an enhancement level up to about 30% is typical and metal particles with less than $w < 1.5\%$ gives an enhancement up to 40%. The thermal conductivity of nanoparticles is more temperature sensitive than that of the base fluid. Consequently, the thermal conductivity enhancement of nanofluids is also rather temperature sensitive and a strong dependence of nanofluid thermal conductivity is due to the random motion of nanoparticles [8].

The thermal conductivity of kerosene based Fe_3O_4 nanofluids increased almost linearly with volume concentration of the nanoparticles [9]. When the volume concentration was 1%, the enhancement value was up to 34%, which was higher than that of Fe_3O_4 aqueous nanofluid. Kerosene based Fe_3O_4 nanofluids prepared did not show the time-dependence of the thermal conductivity characteristic, which indicated a good suspension stability of the nanofluids prepared by them. In order to investigate the effect of temperature on the enhancement of the thermal conductivity, the thermal conductivities were measured in the temperature range of 10–60◦C. The results indicated that the absolute thermal conductivities increased with the increasing temperature with the enhanced ratios being almost constant. Thus it was concluded that the thermal conductivities of the nanofluids track the thermal conductivities of the base liquid. Experimental investigations have been carried out by for determining the thermal conductivity of three nanofluids containing Al_2O_3, CuO and ZnO nanoparticles dispersed in a base fluid of 60:40 (by mass) ethylene glycol and water mixture [10]. Particle volumetric concentration tested was up to 10% and the temperature range of the experiments was from 25◦C to 80◦C. They observed an increase in the thermal conductivity of nanofluids compared to the base fluids with an increasing volume concentration of nanoparticles. The thermal conductivity also increased substantially with an increase in temperature. At room temperature, maximum thermal conductivity enhancement observed with nanofluids containing Al2O3, CuO and ZnO nanoparticles were 35%, 32% and 17% respectively.

2.2 Viscosity

While the thermal conductivity of nanofluids is important for heat transfer applications, viscosity is also important in designing nanofluids for flow and heat transfer applications because the pressure drop and the resulting pumping power depend on the viscosity.A maximum increase in viscosity of Al2O3/water nanofluids was 2.36 times that of water at 5% volume concentration [11]. The results show that the relative viscosity increase was almost linear up to 2% volume concentration. However, at volume concentrations more than 2%, the increase in relative viscosity shows a nonlinear relationship with volume concentration. This was attributed to the hydrodynamic interactions between particles which become important as the disturbance of the fluid around one particle interacts with that around other particles at higher volume concentrations.

The effect due to temperature and particle volume concentration on the dynamic viscosity for the Al2O3/water nanofluid has been experimentally investigated [12]. In general, the nanofluid dynamic viscosity increases considerably with particle volume concentration but decreases with a temperature increase. The existence of a critical temperature beyond which the particle suspension properties seem to be drastically altered, which, in turn, has triggered a hysteresis phenomenon. The hysteresis phenomenon has raised serious doubts regarding the reliability of using nanofluids for heat transfer enhancement purposes.

2.3 Density

Density of nanofluid is proportional to the volume ratio of solid (nanoparticles) and liquid (base fluid) in the system. Since the density of solids is higher than that of the liquids, generally the density of nanofluid is found to increase with the addition of nanoparticles to the fluid. In the absence of experimental data, the density of the nanofluids has been reported to be consistent with the mixing theory given by

$$\rho_{nf} = (1-\varphi)\, \rho_{bf} + \varphi \rho_s$$

Where ρnf= density of nanofluid, ρbf= density of base fluid, ρs = density of solid particles, φ = volume concentration. The density of the Al2O3/propanol nanofluid measured at room temperature using two methods and compared them [13]. In the first method, a hydrometer was used to measure the specific gravity of a fluid sample. In the second method, a fluid sample of known volume was taken and then weighed on a high precision balance. Data collected using these two methods were then averaged and a nearly linear relationship between density and particle concentration was observed.

III. SPECIFIC HEAT

Typically, the nanofluid‘s specific heat is smaller than that of the base fluid which implies that for the same temperature increment, heat energy needed is lesser for nanofluid compared to base fluid. In the absence of available experimental data, the following two models have been extensively applied in the experimental and

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numerical nanofluid investigations to find the specific heat of nanofluid. The first model is one which is analogous to the mixing theory and the specific heat of a nanofluid is expressed as

$$c_{p,} = (1-\varphi)\, c_{p,bf} + \varphi c_{p,s}$$

where the subscripts nf, bf, and s refer to the nanofluid, base fluid and nanoparticle respectively. Because of its simplicity, above equation has been used in the assessment of the heat transfer performance of nanofluids by researchers. The second model is based on thermal equilibrium mechanism and the specific heat of a nanofluid is expressed as

$$c_{\rho nf} c_{p,} = (1-\varphi)\, \rho_{bf} c_{p,bf} + \varphi \rho_s c_{p,s}$$

This equation has also been adopted in nanofluid investigations. In the case that no experimental data are available, it has been believed that both expressions can be considered equivalent and either one may be used to estimate nanofluid specific heat.

IV. MECHANISMS OF ENHANCEMENT OF HEAT TRANSFER

A substantial increase in liquid thermal conductivity, liquid viscosity, and heat transfer coefficient, are the unique features of nanofluids. The thermal conductivity of metallic liquids is much greater than that of non-metallic liquids. Thus, fluids containing suspended metal particles are expected to manifest enhanced thermal conductivities relative to pure fluids. Disperssion of aluminium particles into a fluid resulted in a 100% increase in the thermal conductivity of the fluid for w= 0.5–10% [14]. Cu–ethylene glycol (nanoparticles coated with thioglycolic acid) with w= 0.3% gave a 40% increase in thermal conductivity [3]. Moreover, the effective thermal conductivity depends also on other mechanisms of particle motion; the commonly explained physics are as follows.

4.1 Dispersion of the suspended particles

Dispersion is a system in which particles are dispersed in a continuous phase of a different composition. Surface-active substances (surfactants) can increase the kinetic stability of emulsions greatly so that, once formed, the emulsion does not change significantly over years of storage. Some of the surfactants are thiols, oleic acid, laurate salts, etc. According to [15], [16] and others claimed that the abnormal increase in thermal conductivity is due to uniform dispersion of the nanoparticles.

4.2 Intensification Of Turbulence

Even though thermal conductivity (kth) is a function of primary variables such as thermodynamic pressure and temperature, in a turbulent flow the effective thermal conductivity (kth+kturb) due to the effects of turbulent eddies is many times higher than the actual value of kth. Similarly in nanofluids, such intensification is believed to be possible due to the addition of nanoparticles [16]

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4.3 Brownian Motion

It is a seemingly random movement of particles suspended in a liquid or gas and the motion is due to collisions with base fluid molecules, which makes the particles undergo random-walk motion. Thus, the Brownian motion intensifies with an increase in temperature as per the kinetic theory of particles. The potential mechanism for enhancement of thermal conductivity is the transfers of energy due to the collision of higher temperature particles with lower ones [17]. The effectiveness of the Brownian motion decreases with an increase in the bulk viscosity.

V. Thermophoresis

Thermophoresis or the Sore´t effect is a phenomenon observed when a mixture of two or more types of motile particles (particles able to move) is subjected to the force of a temperature gradient. The phenomenon is more significant in a natural convection process, where the flow is driven by buoyancy and temperature. The particles travel in the direction of decreasing temperature and the process of heat transfer increases with a decrease in the bulk density.

VI. Diffusiophoresis

Diffusiophoresis (also called as Osmo-phoresis) occurs when there is a migration of particles from a lower concentration zone to a higher concentration one. However, this is not a favorable condition since the nanofluids may lose their non-agglomeration characteristics. Thus, the resulting fluid will result in a discrete spread in the particle density. The Brownian motion, thermophoresis and diffusiophoresis are significant in the absence of turbulent eddies [18].

VII. Natural Convection in Nanofluids

As compared to the analytical or numerical work on the natural convection in nanofluids, very less experimental work has been reported in literature. There is a large confliction between the results obtained by the analytical or numerical and experimental work. Enhancement in thermal conductivity is conveyed in literature for all types of work. A high enhancement in heat transfer coefficient as compared to base fluid is reported in analytical and numerical investigation of the natural convection in nanofluids. While maximum experimental research work shown the degradation in the heat transfer coefficient as compared to base fluid. The phenomenon of natural convection in nanofluids explained [19]. The experimental system is shown schematically in Figure 1. It consisted of two horizontally positioned aluminum discs of diameter 240 mm and thickness 10 mm (C and D) separated by a 10 mm gap through a short insulated PTFE cylinder (F). The upper surface of the top aluminum disc was exposed to the open space and cooled by compressed air. The gap between the aluminum discs was filled with nanofluids for convective heat transfer experiments. Six type J thermocouples (T1–T6) and two surface heat flux sensors (I) were mounted on the aluminum surfaces to measure temperatures and heat fluxes. The thermocouples and heat flux sensors were connected to a data acquisition system (K). The heat flux was obtained from the input voltage and resistance of the heater by

$$q= U^2/(RA)$$

where U is the voltage, R is the resistance of the heater, and A is the surface area of the heater, which is the same as the surface area of the bottom aluminium disc (and also that of the top disc). At the steady state, the heat diffusion equation was adopted to obtain the surface temperatures of both the upper surface of the bottom disc (Tub) and the lower surface of the top disc (Tlt)

$$T_{ub} = T_{mh} - qd/ ,$$
$$T_{lt} = T_{mc} - qd/k_w$$

where Tlb is the temperature of the lower surface the bottom disc, Tut the temperature of the upper surface of the top disc, d is the thickness of the discs, and kW is the thermal conductivity of the discs. The heat transfer coefficient, h, was calculated by

$$h = q/(T_{ub} - T_{lt})$$

Wen et al. [19] concluded that the Nusselt number decrease continuously with time while the Rayleigh number increases during the heating period. They found deterioration in natural convective heat transfer coefficient increases with nanoparticle concentrations. The effect of the distribution of particle size ofthe natural convection of water-fine particle suspension in a rectangular cell heated and cooled from opposing vertical walls investigated [20]. Two kinds of nanoparticles used to make suspensions: micro beads made of soda glass (A) (specific gravity = 2.5) and micro beads made of SiO2 (B) (specific gravity = 2.15). In the case of a suspension which has a particle size distribution, many layers separated by almost horizontal interfaces are formed in the initial stage of natural convection. Each interface of layers falls gradually with a constant velocity and the number of the layers decreased with time and finally all layers vanished. Each layer had a circular flow and the flow in a layer did not enter into neighboring layers. The concentration of particles in each layer was almost uniform and the lowest layer had the largest concentration and the largest mean diameter of particles. When the particle size distribution was narrow, formation of the layers was depressed. The natural convective heat transfer of Fe3O4/Ethylene Glycol nanofluids in the presence of the electric field around a thin platinum wire examined [21]. Addition of nanoparticles to ethylene glycol promoted heat transfer up to the volume fraction of 0.02%. An increment in the volume fraction resulted in deteriorated heat transfer. An electric field was used to intensify the natural convective heat transfer of both ethylene glycol and nanofluids. By applying an electric field, an increased enhancement experienced while decreased with Rayleigh number. Electric field delayed the deterioration of heat transfer of nanofluids to greater volume fractions.

The natural convection heat transfer of alumina-water nanofluid in vertical square enclosures has been investigated [22]. Three vertical square enclosures of different cross-section used. The nanofluid formulated was water dispersed with various volumetric fractions of the alumina (Al2O3, size 33nm) nanoparticles ranging from 0.1 vol.% to 4 vol.%. The variation in Rayleigh number was in the range of 6.21 X 105- 2.56 X 108. A heat transfer enhancement of around 18% compared with that of water was found for the nanofluid containing much lower particle fraction of 0.1 vol.% in the large enclosure at sufficiently high Rayleigh number. A relative increase of up to 55% in the dynamic viscosity arose for the nanofluid containing 4 vol.% of nanoparticles with respect to the base fluid (water). The relative changes in the thermo-physical properties of the nanofluid with respect to its base fluid affected the heat transfer efficacy of using nanofluid for natural convection in an enclosure. The thermophoresis could be non-negligible in the nanofluid, inducing the depletion and accumulation of nanoparticles, respectively, near the hot wall and the cold wall of the enclosure and thus developing two thin concentration boundary layers. An experimental investigation on natural convection heat transfer inside vertical circular enclosures has been carried out and used Al2O3 (size 10nm) nanofluid with different concentrations; 0.0%, 0.85% (0.21%), 1.98 (0.51%) and 2.95% (0.75%) by mass (volume) [23]. Results concluded that heat transfer coefficient increased as the concentration increased up to a specific value of the concentration and then it started to decrease with the volume concentration. Enhancement in Nu occurs for volume fraction >0.51% (vol.) and deterioration in Nu is obtained beyond that due to dominated effect of viscosity for high volume concentration. The enhancement in heat transfer coefficient at a lower aspect ratio is high than at high aspect one.

VIII. Applications of Nanofluids

Nanofluids can be used in broad range of engineering applications due to their improved heat transfer and energy efficiency in a variety of thermal systems. The following section gives a brief idea of different areas of nanofluid applications based on available literatures [24]. 3.1. Applications in Automotive Nanofluids have wide application in automobiles. These can be used as brake fluid, engine coolant, transmission fluid etc. Smaller size radiators will be required if the nanofluids will be used as a coolant 3.2. Applications in Domestic Refrigerator Working fluid properties and energy efficiency of the refrigeration system can be improved by using nanofluids. 3.3. Space and Defense Due to the restriction of space, energy and weight in space station and aircraft, there is a strong demand for high efficient cooling system with smaller size. So nanofluids can be a promising tool for the same. A number of military devices and systems require high-heat flux cooling to the level of tons of MW/m2. For reliable operation cooling of military devices is very essential. Due to high heat flux of nanofluids, they have the potential to provide the required cooling in military systems. 3.4. Electronic Applications In electronic components due to small size and large number of chips the heat production is high but removal is very difficult. Advancement in electronics industry made heat rejection very difficult due to day by day smaller surface area. Nanofluids have potential to increase the rate of heat removal and make the operation smooth. 3.5. Solar Devices In water heating applications, direct heating solar collectors have been proposed. But due to non availability of efficient working fluids this technology is far from reality. Nanofluids are the promising fluid for such type of application. Efficiency improvement of 5% is achieved by using nanofluids. 3.6. Industrial Cooling Applications Reduced emissions from the industries and large energy savings can be achieved with the use of nanofluids. For the electric power industry using nanofluids could save about 3000-9000 million kWh of energy per year. Some of the challenges of nanofluid to make them practically feasible are as follows- poor long term stability, increased pressure drop and pumping power, low specific heat and high cost.

IX. Conclusion

Addition of nanoparticles to a liquid increases the viscosity significantly and the thermal conductivity moderately, however the specific heat and density changes modestly. Prandtl number of nanofluids increases as particle volume concentration increases, but decreases with an increase in the temperature. Reynolds number of nanofluid for a specified geometry and velocity increases with temperature and decreases with an increase in particle volumetric concentration. The convective heat transfer coefficient of nanofluids increases with an increase in temperature and concentration and is significantly higher than that of the base fluid. There exists an optimal range of temperature and concentration at the dilute level, where the benefits of nanofluids can be maximized. In general, nanofluids show many excellent properties promising for engineering application. But there are still several important issues that need to be solved for applications of nanofluids in engineering.

[1.] Although many nanofluid systems have been prepared, nanofluid systems with special properties that can meet practical engineering requirement have not been developed.

[2.] The long-term stability of nanofluids is a key issue for both scientific and practical applications. To date, the long-term stability of most studied nanofluids is not confirmed and more basic theoretical and experimental work is required for improving the stability of nanofluids.

[3.] The factors influencing enhancement of thermal conductivity of nanofluids need to be investigated systematically. The mechanism influencing the thermal conductivity of nanofluids is still unknown although many models have been proposed to deal with the abnormal increase in thermal conductivity of nanofluids.

[4.] No uniform standard was presented for experimental research on nanofluids, including the preparation of nanofluids, the thermal conductivity measurement of nanofluids and the stability evaluation of nanofluids.

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