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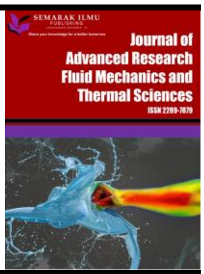

The Investigation of Thermoacoustic Methods for Nanofluid Stability on Heat Exchanger

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ABSTRACT

Due to various engineering applications, nanofluids have gained much attention in the last decade. A Nanofluid is a nanometer-sized particle such as metal, oxide, carbide, etc., dispersed into a base heat transfer fluid. The heat exchanger is a device to transfer heat between fluids. Heat exchanger plays a very important role in modern industry. The new innovative fluid called nanofluid is introduced to improve the overall heat transfer and heat transfer rate. Thermoacoustic is a system which uses sound waves and a non-flammable mixture of inert gases to generate an effect. This paper investigates the enhancement of the heat transfer coefficient of a nanofluid containing alumina (Al_2O_3) nanoparticle with a volume fraction of 0.4% and sonification at 100 Hz, 500 Hz and 1000 Hz. The addition of Al_2O_3 nanoparticles will affect the characteristics of the nanofluids, which affect the values of density, specific heat, thermal conductivity, and dynamic viscosity. And the addition of the thermoacoustic method with the sonification of acoustic waves can stabilise the effect of Brownian motion in the nanofluid flow. The maximum results are obtained using acoustic waves at 1000 Hz at high temperatures.

1. Introduction

Choi and Eastman were the first to name such fluids as nanofluids. Nanofluids are the engineered colloidal suspension of nanoscaled particles (10-100 nm) in a base fluid. These particles are generally metals, metallic oxides or other carbon-based elements. Nanofluids are often used as heat carriers in heat transfer equipment [1]. Examples of important uses of heat transfer fluids include vehicular and avionics cooling systems in the transportation industry, hydronic heating and cooling systems in buildings, and industrial process heating and cooling systems in petrochemical, textile, pulp and paper, chemical, food and other processing plants. Nanofluids are expected to exhibit superior properties compared to conventional heat transfer fluids and fluids containing micrometre-sized metallic particles [2,3].

Conventional micron-sized particles cannot be used in practical heat transfer equipment because of severe clogging problems [4]. However, nanophase metals are believed to be ideally suited for

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applications in which fluids flow through small passages because the metallic nanoparticles are small enough to behave similarly to liquid molecules [5]. Therefore, nanometre-sized particles will not clog flow passages but will improve the thermal conductivity of the fluids [6].

Low thermal conductivity is a primary limitation in the development of energy-efficient heat transfer fluids that are required in many cooling applications. However, it is well known that at room temperature, metals in solid form have orders of magnitude higher thermal conductivities than those of fluids. Therefore, the thermal conductivities of fluids that contain suspended solid metallic particles are expected to be significantly enhanced over those of conventional heat transfer fluids [7].

In developing energy-efficient heat transfer equipment, the thermal conductivity of the heat transfer fluid plays a vital role [8,9]. However, traditional heat transfer fluids, such as water, oil, and ethylene glycol mixtures, could be better heat transfer fluids. With increasing global competition, industries strongly need to develop advanced heat transfer fluids with significantly higher thermal conductivities than are presently available [10,11].

Over a century ago, Maxwell [12] was the first to discuss the suspension of micro-scaled particles into a fluid. However, microparticles settled rapidly in the fluid leading to abrasion and clogging in the flow channel, limiting further research into fluid suspensions. Furthermore, these fluids did not exhibit the significant enhancement witnessed today using nanofluids. The introduction of nanoparticles has allowed for further investigation into colloidal dispersion in fluids. Nanoparticles are more stable when dispersed in fluids and tend to improve the thermal properties of the fluids. Some other properties of nanofluids that make them adequate heat transfer fluids include the Brownian motion of particles, particle/fluid nanolayers and their reduced pump power compared to pure liquids to achieve intensified heat transfer.

Nanofluids can be unstable due to the strong Van der Waals interactions and cohesive forces between nanoparticles. Therefore, the preparation technique used is extremely important in others to break down these forces and produce stable nanofluids. Different methods have been used to avoid nanoparticle aggregation and improve the stability of nanofluids, such as pH control, surfactant addition, ultrasonic agitation, magnetic stirring, functionalisation and high-pressure homogenisation [13].

The main factors affecting the thermophysical properties of nanofluids include the morphology and concentration of nanoparticles, aggregation in the nanofluids and the sonication time used in its preparation [14]. The stability of nanoparticles suspended in a fluid is a very important parameter affecting the rheological and thermophysical behaviours of the resultant nanofluids. Brownian motion causes the particles to collide, leading to cluster formation in the base fluid. Various internal forces between the base fluid and the nanoparticles control these cluster formations or aggregations, such as the Van der Waals forces of attraction between the particles.

The aggregates begin to crystallise as their density exceeds that of the base fluid and affects the stability of the nanofluids over time. Some of the factors that affect the stability of the nanofluids include the method of preparation of the nanofluids, agitation and sonication time [15], pH of the nanofluids, the addition of surfactants [16] and surface charge density of the nanoparticles [14]. The effect of sonication on the stability and thermophysical properties of nanofluids. The study concluded that while an optimum sonication time exists where thermal conductivity is maximum and viscosity is least, more research is required to determine this optimum value, as it appears to differ for different nanofluids. The effects of nanoparticle synthesis techniques on nanofluids' stability and thermophysical behaviour. The study noted that there appears to be no standard method for stability measurements; this makes it difficult to compare stability across different papers; this is a problem because of the significant differences in reported fluid stability; which can range from days in some studies to months in others.

Mahyari *et al.,* [17] investigated the thermal conductivity of GO/SiC (50:50)/water hybrid nanofluid at volume concentrations between 0.05 and 1%. Their investigation reveals that the effect of the volume concentration of nanoparticles was more significant than the effect of increasing temperature. Importantly, the studies observed that the enhancement in thermal conductivity of their hybrid nanofluid was more than the reported thermal conductivity enhancement using GO or SiC individually. Hybrid nanofluids not only affect thermal conductivity but also enhance the stability of nanofluids.

The main benefit of using nanofluids is their enhanced thermal transport which results in improvements in the thermal conductivity of traditional heat transfer fluids. As previously outlined, several parameters influence the thermal conductivity enhancement, including nanoparticle type, nanoparticles size, nanoparticles concentration, temperature, type of base fluid and the thermophysical properties of both the base fluid and the nanoparticles. Over the last three decades, since the introduction of nanofluids in 1995, the explanations behind the enhanced heat transfer of nanofluids have been attributed to several mechanisms. The size and the large number of particles interacting with the base fluid present a challenge to properly understanding the nanoscale effects that support the improved thermal properties observed in the literature. Mahian *et al.,* [18] studied the mechanisms that would aid the simulation of nanofluid flow. They highlighted that forces such as drag, lift, Brownian motion, thermophoresis, Van der Waals, and electrostatic double-layer forces had a significant effect on nanofluids' thermal and rheological behaviours.

Brownian motion is the uncontrollable random motion of particles within the fluid due to the collision between slow-moving and higher-velocity particles. Brownian motion occurs as a result of thermal diffusion, and this phenomenon is increased at higher temperatures, low viscosity and smaller particle size. As promoted by the scientific community, the random collision of particles within the fluid remains the primary reason for the thermal conductivity enhancement observed with nanofluids [17]. However, Jang and Choi [19] provided three types of collisions that occur due to the rising temperature of nanofluids: collisions between the molecules of the base fluid, collisions between base fluid molecules and the nanoparticles, and collisions between nanoparticles due to Brownian motion. They concluded that the effect of Brownian motion on thermal conductivity enhancement had the least effect among the three types of collisions.

Keblinski *et al.,* [20] were the first to introduce the idea of nanolayers and their effect on nanofluid thermophysical behaviour. The nanolayer is the solid-like structure or the interfacial layer between the solid surface and the first layer of the fluid in contact with the solid surface. A structured, layered arrangement of the fluid molecules around the surface of the nanoparticles was observed. These layers behave like solids and act as a thermal bridge for the heat transfer process, enhancing the overall thermal conductivity of the fluid. This layer acts as a barrier to heat transfer in the solid-solid interface due to incomplete contact between solid surfaces. However, this is not the case for the solid–liquid interface, as the aligned interfacial shell in the nanoparticle suspension would make heat transfer effective.

2. Experimental Setup and Procedure

This research employs a double-pipe heat exchanger with a round pipe. The flow direction is counter flow, which is more efficient at transferring heat than parallel flow. This heat exchanger comprises primary components and supporting components such as measuring equipment. Al_2O_3 nanoparticles were used in this investigation. This study manufactures nanofluids by combining aluminium nanoparticles Al_2O_3 with pure water in a 12 litres water reservoir at a volume fraction concentration of 0.4%. The nanoparticles that have become dry powder are disseminated in the base fluid during this step (water). Magnetic stirring is used to mix essential fluids with nanoparticles. Magnetic stirrers comprise two components: the magnetic stirrer and the stirring bar. The stringing bar utilised in this study was 15x40 mm. If the resulting nanofluid still includes deposits of nanoparticles after standing, the nanofluid must be agitated again to distribute the nanoparticles in the base fluid and prevent aggregation. The nanofluid cooling fluid Al_2O_3 temperature is 30℃, whereas the hot fluid is 90℃.

The temperature of the nanofluid was determined in this work using a thermocouple and thermometer. After thoroughly mixing the nanoparticles with the base fluid with a magnetic stirrer, the nanofluid is introduced into the reservoir and evenly stirred. It is done to prevent the nanoparticles from settling rapidly. The pump will be turned on to drain it, and the fluid will be pumped into the double-pipe heat exchanger.

In this investigation, a constant flow rate was achieved by opening the valve and measuring the flow rate with a flowmeter. While the fluid is flowing, the speakers are also controlled via the laptop's tone generator software, which generates high-frequency acoustic waves. After the temperature has stabilised, the thermometer component records the data. At each frequency, the temperature is recorded. Every 15 seconds, data was collected to determine the value of the temperature reduction. The double pipe heat exchanger of the counter flow type. It has been fitted with speakers and sealed to create a tight space. The schematic diagram of this testing apparatus is depicted in Figure 1.

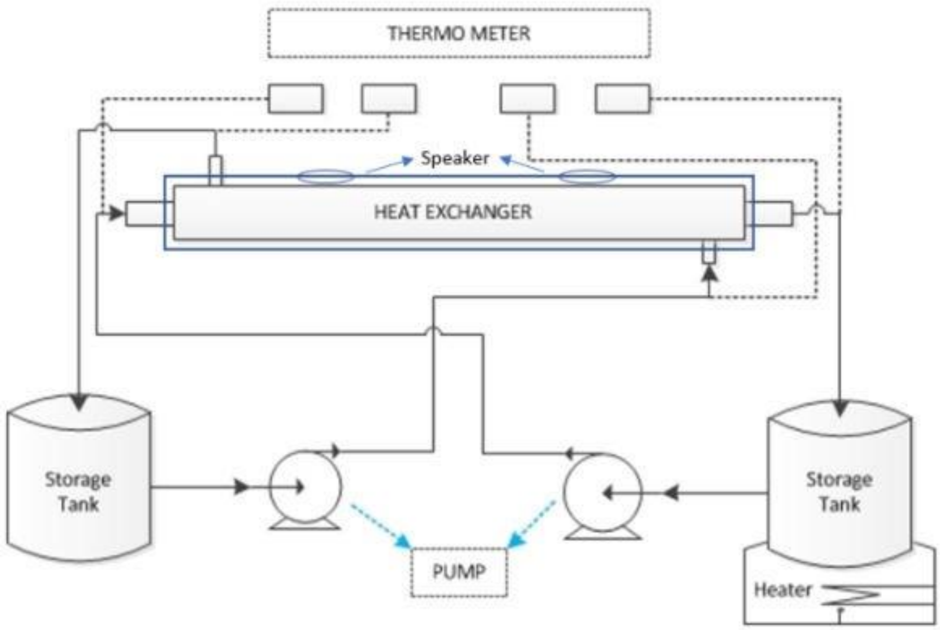

Fig. 1. Schematic of experimental setup

Two water reservoirs for hot water are heated via a heater, and a cooling fluid reservoir with a capacity of 12 litres is filled with a mixture of water and nanofluids. The reservoir fluid will be pumped to the heat exchanger tube using a pump with a discharge rate of 24 lpm. This counter-flow heat exchanger tube has two active speakers that generate sonic waves at 100 Hz, 500 Hz, and 1000 Hz, respectively. Four types of k thermocouples are used in this test, one on each side of the intake and outflow. The thermocouple will measure the temperature of the fluid passing through it, which will be displayed on a thermometer. The fluid temperature displayed on a digital thermometer display is recorded and processed.

The test equipment consists of a double-pipe counter flow heat exchanger with a straight brass (brass) pipe of 1200 mm in length, 1 mm in thickness, 31.7 mm in outer diameter, and 29.7 mm in inner diameter for hot fluids. Straight stainless-steel pipe 1000 mm in length, 2 mm in thickness, 101.6 mm in outer diameter, and 97.7 mm inner diameter for the cooling fluid. The test device has two separate pipes for the hot and nanofluid cooling fluids. Additionally, there are two centrifugal pumps for the transfer of heated fluids and aluminium nanofluids Al_2O_3. Two fluid storage tanks are provided, one for hot fluid and another for nanofluid cooling fluid. The cooling fluid distribution pipe to the heat exchanger has a diameter of 12.7 mm, as does the anti-heat hose used to transport hot fluid from the heated tank.

The heated fluid in the tank will then be sucked in and pumped through a 1200 mm long pipe to the heat exchanger's entrance by a hot fluid pump. While the nanofluid in the tank is sucked and circulated through a 1000 mm long pipeline by the cooling water pump to the heat exchanger's cooling intake. Figure 2 illustrates the double-pipe heat exchanger employed in this investigation.

Fig. 2. A Double pipe heat exchanger

Table 1 indicates the specification of the outer pipe.

Table 1
Straight circular outer pipe specifications

Property	Size	Unit
Outer diameter (D_o)	101.7	mm
Inner diameter (Di)	97.7	mm
Thick (t)	2	mm
Length (L)	1000	mm
Thermal conductivity (k)	16	W/mK
Material		SS 304

Table 2 specifies the inner pipe.

Table 2
Straight circular outer pipe specifications

Property	Size	Unit
Outer diameter (D_o)	31.7	mm
Inner diameter (Di)	29.7	mm
Thick (t)	1	mm
Length (L)	1200	mm
Thermal conductivity (k)	110	W/mK
Material		Cooper

It is necessary to know the thermophysical parameters of nanofluids to predict their behaviour or heat transmission behaviour. Nanofluids exhibit distinct thermophysical, rheological, and thermoelectric properties compared to normal fluids. These qualities are impacted by the nanoparticles' substantial specific surface area.

The convection heat transfer equation is known as Newton's Law of Cooling, where for all heat transfer mechanisms, if the temperature difference between the object and its surroundings is small, then the cooling rate of an object is almost proportional to the temperature difference, which is formulated as follows:

$$h = N_u \frac{K}{D} \tag{1}$$

where h is convection heat transfer coefficient (W/m^2.K), N_u is Nusselt number, K is thermal conductivity (W/m·K), and D is pipe diameter (m).

$$U = \frac{1}{\frac{1}{h_i}+\frac{1}{h_o}} \tag{2}$$

where U is the total overall convection heat transfer coefficient (W/m^2·K), h_i is the inner convection heat transfer coefficient (W/m^2·K), and h_o is the outer convection heat transfer coefficient (W/m^2·K). Using Eq. (3) and Eq. (4) to obtain the values of ΔT_1 and ΔT_2:

$$\Delta T_1 = T_{hi} - T_{co} \tag{3}$$

$$\Delta T_2 = T_{ho} - T_{ci} \tag{4}$$

where $\Delta T1$ is the difference in temperature between the hot water inlet and the cold-water outlet, ΔT_2 is the difference in temperature between the hot water outlet and the cold-water inlet, T_{hi} is the temperature of the hot water inlet, T_{ho} is the temperature of hot water outlet, T_{ci} is the temperature of cold-water inlet, and T_{co} is the temperature of the cold-water outlet.

The quantity indicates the volume of fluid flowing through a cross-section per unit of time. The rate of flow can be expressed in:

$$Q = \frac{V}{t} \tag{5}$$

where V is flow volume (m^3), Q is flow rate (m^2/s), and t is flow time(s). Fluid velocity (u) is the flow rate flowing per unit area.

$$Q = \frac{V}{t} \tag{6}$$

where v is the flow rate (m/s), and A is the cross-sectional area (m^2).

The density of a substance is defined as the amount of that substance contained in a unit volume. The density of nanofluids is proportional to their particle volume fraction. The rise in density is related to the increase in particle volume fraction. Density reduces non-linearly as fluid temperature increases. The fundamental explanation for this non-linear behaviour is the difference in the thermal expansion coefficients of the base fluid and nanoparticles. The density of a liquid decreases in a non-linear manner as the temperature of the liquid increases. It occurs due to the difference in thermal expansion coefficients between the base liquid and the nanoparticles. Additionally, the following equation can be used to compute the density of nanofluids:

$$\rho_{nf} = \varphi\rho_p + (1-\varphi)\rho_{bf} \tag{7}$$

where ρ_{nf} is the density of nanofluid (kg/m^3), φ is the volume fraction of nanoparticles (%), ρ_{bf} is the density of the base fluid (kg/m^3), and ρ_p is the density of nanoparticles (kg/m^3).

The nanofluid's specific heat can be determined using the following equation for any volume concentration of nanoparticles in the base fluid:

$$Cp_{nf}.\rho_{nf} = \varphi(\rho_p.Cp_p) + (1-\varphi)(\rho_{bf}.Cp_{bf}) \tag{8}$$

where Cp_{nf} is specific heat nanofluid (J/kg·K), Cp_{bf} is specific heat base fluid (J/kg·K), Cp_p is specific heat nanoparticles (J/kg·K), ρ_{bf} is the density of the base fluid (kg/m^3), and ρ_p is the density of nanoparticles (kg/m^3).

Thermal conductivity is a quantitative property of a material that indicates how well it conducts heat. The following equation can be used to get the thermal conductivity of nanofluids using the Maxwell model:

$$\frac{k_{nf}}{k_{bf}} = \frac{k_p+2.k_{bf}-2.(k_{bf}-k_p).\varphi}{k_p+2.k_{bf}+2.(k_{bf}-k_p).\varphi} \tag{9}$$

where k_{nf} is the thermal conductivity of nanofluid (W/m·K), k_p is the thermal conductivity of nanoparticles (W/m·K), kbf is the thermal conductivity of the base fluid (W/m·K), and φ is concentration or volume fraction of nanoparticles.

Viscosity is a term that refers to the internal resistance of a fluid to flow, and it is a critical attribute for all thermal applications that use fluids. The fluid's viscosity depends on the pumping force, pressure drop in laminar flow, and convective heat transfer. The viscosity of nanofluids with a volume fraction less than 4% can be determined using the Brinkman model's proposed equation below:

$$\mu_{nf} = \frac{1}{(1-\varphi)^{2,5}} \cdot \mu_{bf} \tag{10}$$

where μ_{nf} is nanofluid dynamic viscosity (kg/m·s), μ_{bf} is the dynamic viscosity of the base fluid (kg/m·s), and φ is the volume fraction of nanoparticles (%).

Reynolds Number is a physical quantity that has no dimensions. This value is used to classify the flow as laminar, turbulent, or transitional. Four parameters influence whether a flow is laminar or turbulent: water density, flow velocity, viscosity, and pipe diameter. The sum of these four values yields the Reynolds number. The value of the Reynolds Number (Re) for flow in a pipe is determined:

$$Re = \frac{\rho.v.D}{\mu} \tag{11}$$

where R_e is Reynolds Number, v is flow velocity (m/s), μ is fluid dynamic viscosity (Ns/m^2). Then, the Reynolds number for nanofluid becomes:

$$Re_{nf} = \frac{\rho_{nf}.v.D}{\mu_{nf}} \tag{12}$$

The Prandtl Number is the fluid's kinematic viscosity ratio to its heat diffusivity. The Prandtl number denotes the fluid's thermodynamic property as determined by the following equation:

$$\mathrm{Pr} = \frac{v}{\alpha} = \frac{\mu C_p}{k} \tag{13}$$

where P_r is Prandtl number, u is the kinematic viscosity of the fluid (m^2/s), α is thermal diffusivity (m^2/s)c, C_p is specific heat fluid (J/Kg·K), μ is the dynamic viscosity of the fluid (kg/m·s), and k is the thermal conductivity of the fluid (W/m·K). Then, the Prandtl number for nanofluid becomes:

$$Pr_{nf} = \frac{\mu_{nf} Cp_{nf}}{k_{nf}} \tag{14}$$

The Nusselt number (Nu) is the ratio of a fluid's convective heat transfer to its conduction heat transfer under identical surface circumstances and a non-dimensional temperature gradient on the surface.

$$N_u = 0.023 \cdot {R_e}^{4/5} . {P_r}^{n} \tag{15}$$

n is 0.4 for heating and 0.3 for cooling.

3. Results and Discussion

In this study, nano-sized Al_2O_3 particles were mixed with water in a 12-litre container with a volume concentration of 0.4%. The cooling fluid of a mixture of water and nanoparticles will have flowed in a 12-litre reservoir using a pump to a heat exchanger pipe measuring 0.0977 m in diameter. Table 3 show the required mass of alumina nanoparticle.

Table 3
The required mass of nanoparticles at a volume concentration (ϕ= 0,4%)

Concentration (%)	The volume of Nanoparticle (ml)	Mass of Nanoparticle (grams/L)	Mass of Nanoparticle (grams/12L)
0.4	4	15.88	190.56

Figure 3 show Alumina nanoparticle.

Fig. 3. Al_2O_3 Nanoparticles

In straight round pipes, hot fluid with Al_2O_3 nanofluid cooling fluid with concentrations of 0.4% resulted in a higher convection heat transfer coefficient at the largest frequency, 1000 Hz. Based on Figure 4, it can be seen that the Reynolds number increases steadily with increasing temperature. The addition of acoustic waves with a frequency of 100 Hz to produce a sound of 58.2 dB, a frequency of 500 Hz to produce a sound of 61.2 dB, and a frequency of 1000 Hz to produce a sound of 63 dB.

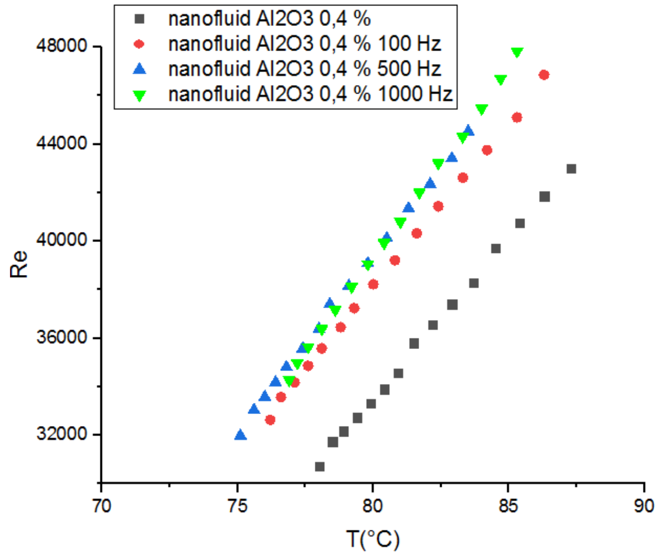

Fig. 4. Relation of R_e-T on nanofluid with concentration (ϕ) 0,4%

Figure 5 is a graph of the Nusselt Number against temperature. Based on Figure 5, the Nusselt number increases steadily as the temperature increases. The comparison graph of the Nusselt number with the temperature below shows the value of the Nusselt number at a lower temperature in nanofluid with the addition of acoustic waves with a higher frequency of 500 Hz, but at higher temperatures, the Nusselt number in nanofluids with the addition of acoustic waves with a frequency of 1000 Hz the Nusselt number increases.

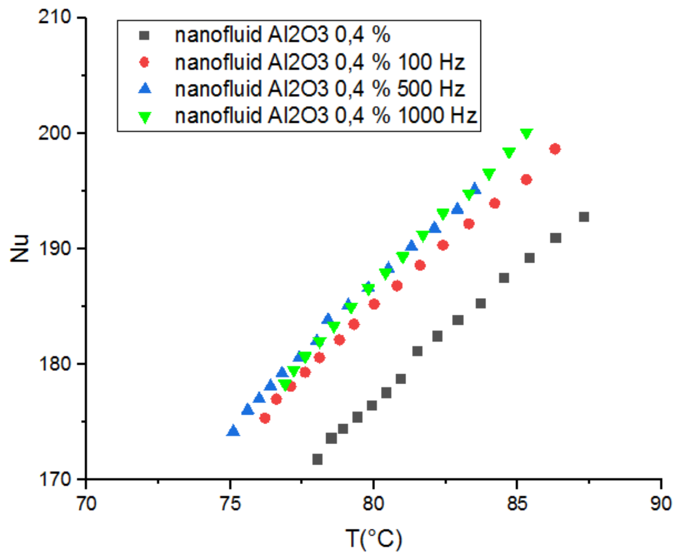

Fig. 5. Relation of N_u-T on nanofluid with concentration (ϕ) 0,4%

Figure 6 shows the convection heat transfer coefficient with 0.4% nanofluid. It can be seen that the convection heat transfer coefficient increases with increasing temperature; this means that heat transfer or heat absorption occurs during the process. Adding nanoparticles to the cooling fluid increases the thermal conductivity so that the heat transfer process increases. The convection heat transfer coefficient with 0.4 percent nanofluid is shown in Figure 6. As the temperature increases, the convection heat transfer coefficient increases. It means that during the procedure, heat transfer or absorption occurs. Including nanoparticles in the cooling fluid increases its thermal conductivity, enhancing heat transfer.

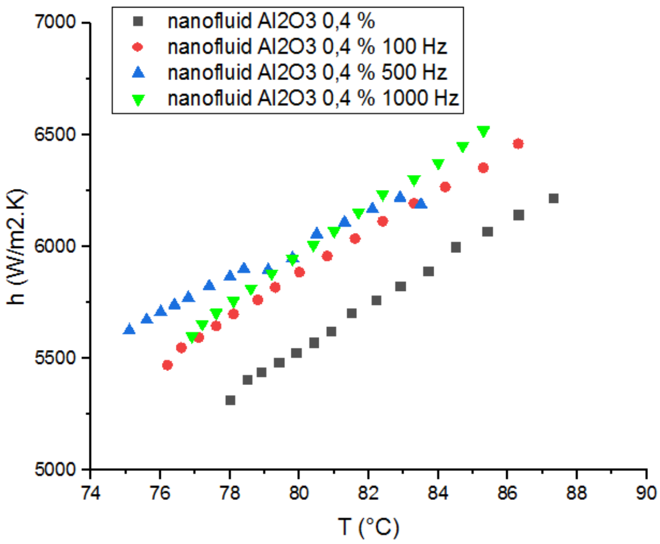

Fig. 6. Relation of h-T on nanofluid with concentration (ϕ) 0,4%

The effect of Brownian motion in nanofluid influences increasing the convection coefficient of nanofluid; this occurs when nanometre-sized particles (10-9) move randomly and float in the base fluid, which causes an increase in the value of thermal conductivity. The brown motion effect also makes the deposition or agglomeration process slow down, reducing the chance of blockage in the pipeline.

Agglomeration is the agglomeration between particles caused by the attractive force of attraction between them. So, it causes a deposition that occurs in the basic fluid; in this study, Al_2O_3 nanoparticles with various concentrations were mixed with the basic fluid, namely water (H2O). Each of these nanofluids is put into a bottle so that the process of agglomeration or settling can be visually seen. Agglomeration can harm the stability of the nanofluid because, of course, it will hamper the ability of the nanofluid, and the heat transfer becomes less effective.

Agglomeration will cause nanoparticles to precipitate or sediment, making the nanofluid clear. The factors affecting the settling speed are particle concentration, particle size and density. Low-concentration nanofluids agglomerate faster than high concentrations, and the higher the volume fraction of nanoparticles, the longer the accumulation of nanofluids.

At low concentrations, the nanoparticles in the nanofluid agglomerate relatively quickly, while the nanofluid in the high-concentration agglomerates have formed visually. However, it takes longer for the entire agglomerated nanoparticles to become clear than at low concentrations. And with the addition of acoustic waves, the agglomeration process also slows down.

The agglomeration process in this experiment was sonified by adding acoustic waves of 100 Hz, 500 Hz and 1000 Hz, respectively, to slow down the agglomeration process. Agglomeration that occurs with the addition of acoustic waves takes longer than without sonification; this is because, during the sonification treatment, the nanofluid has a Brownian motion effect so that the nanoparticles in the water float longer.

4. Conclusions

Acoustic waves in the nanofluid flow in a double-pipe heat exchanger can adjust Brownian motion and nanofluid stability. The thermoacoustic approach combined with the sonification of acoustic waves can stabilise the Brownian motion phenomenon in a nanofluid flow. The best results are obtained using acoustic waves with a frequency of 1000 Hz, including sonification results in a more stable Brown motion effect, slowing down nanofluids' aggregation. Thus, the heat absorption process by nanofluids is superior to that of heat absorption without sonification.

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References

[1] Fekadu, Birlie, and H. V. Harish. "Numerical Studies on Thermo-Hydraulic Characteristics of Turbulent Flow in a Tube with a Regularly Spaced Dimple on Twisted Tape." *CFD Letters* 13, no. 8 (2021): 20-31. https://doi.org/10.37934/cfdl.13.8.2031

[2] Choi, S. US, and Jeffrey A. Eastman. *Enhancing thermal conductivity of fluids with nanoparticles*. No. ANL/MSD/CP-84938; CONF-951135-29. Argonne National Lab.(ANL), Argonne, IL (United States), 1995.

[3] Teh, Yuan Ying, and Adnan Ashgar. "Three dimensional MHD hybrid nanofluid Flow with rotating stretching/shrinking sheet and Joule heating." *CFD Letters* 13, no. 8 (2021): 1-19. https://doi.org/10.37934/cfdl.13.8.119

[4] Rusdi, Nadia Diana Mohd, Siti Suzilliana Putri Mohamed Isa, Norihan Md Arifin, and Norfifah Bachok. "Thermal Radiation in Nanofluid Penetrable Flow Bounded with Partial Slip Condition." *CFD Letters* 13, no. 8 (2021): 32-44. https://doi.org/10.37934/cfdl.13.8.3244

[5] Elfaghi, Abdulhafid MA, Alhadi A. Abosbaia, Munir FA Alkbir, and Abdoulhdi AB Omran. "CFD Simulation of Forced Convection Heat Transfer Enhancement in Pipe Using Al_2O_3/Water Nanofluid." *Journal of Advanced Research in Numerical Heat Transfer* 8, no. 1 (2022): 44-49. https://doi.org/10.37934/cfdl.14.9.118124

[6] Eastman, Jeffery A., U. S. Choi, Shaoping Li, L. J. Thompson, and Shinpyo Lee. "Enhanced thermal conductivity through the development of nanofluids." *MRS Online Proceedings Library (OPL)* 457 (1996): 3. https://doi.org/10.1557/PROC-457-3

[7] Lee, S., and S. U. Choi. "S. Application of metallic nanoparticle suspensions in advanced cooling systems." *Recent advance in solids/structures and application of metallic materials, ASME MD-72* (1996): 227-234. https://doi.org/10.1115/IMECE1996-0161

[8] Kumar, T. Prasanna. "Heat Transfer of SWCNT-MWCNT Based Hybrid Nanofluid Boundary Layer Flow with Modified Thermal Conductivity Model." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 92, no. 2 (2022): 13-24. https://doi.org/10.37934/arfmts.92.2.1324

[9] Azwadi, CS Nor, and I. M. Adamu. "Turbulent force convective heat transfer of hybrid nano fluid in a circular channel with constant heat flux." *Journal of Advanced Research in Fluid Mechanics and Thermal Sciences* 19, no. 1 (2016): 1-9.

[10] Choi, Stephen U-S. *Nanofluid technology: current status and future research*. No. ANL/ET/CP-97466. Argonne National Lab.(ANL), Argonne, IL (United States), 1998.

[11] Reddy, Thummala Sankar, P. Roja, S. Mohammed Ibrahim, Giulio Lorenzini, and Nor Azwadi Che Sidik. "Characteristic of Thermal Radiation on MHD Fluid Stream of Nano-Fluid over an Exponentially Elongating Sheet by Means of Warm and Mass Fluxes." *CFD Letters* 14, no. 4 (2022): 80-90. https://doi.org/10.37934/cfdl.14.4.8090

[12] Maxwell, James Clerk. *A treatise on electricity and magnetism*. Vol. 1. Clarendon press, 1873.

[13] Yu, Wei, and Huaqing Xie. "A review on nanofluids: preparation, stability mechanisms, and applications." *Journal of nanomaterials* 2012 (2012): 1-17. https://doi.org/10.1155/2012/435873

[14] Qiu, Lin, Ning Zhu, Yanhui Feng, Efstathios E. Michaelides, Gaweł Żyła, Dengwei Jing, Xinxin Zhang, Pamela M. Norris, Christos N. Markides, and Omid Mahian. "A review of recent advances in thermophysical properties at the

nanoscale: From solid state to colloids." *Physics Reports* 843 (2020): 1-81. https://doi.org/10.1016/j.physrep.2019.12.001

[15] Cacua, Karen, SM Sohel Murshed, Elizabeth Pabón, and Robison Buitrago. "Dispersion and thermal conductivity of TiO 2/water nanofluid: Effects of ultrasonication, agitation and temperature." *Journal of Thermal Analysis and Calorimetry* 140 (2020): 109-114. https://doi.org/10.1007/s10973-019-08817-1

[16] Keklikcioglu Cakmak, Nese. "The impact of surfactants on the stability and thermal conductivity of graphene oxide de-ionized water nanofluids." *Journal of Thermal Analysis and Calorimetry* 139, no. 3 (2020): 1895-1902. https://doi.org/10.1007/s10973-019-09096-6

[17] Mahyari, Amirhossein Ansari, Arash Karimipour, and Masoud Afrand. "Effects of dispersed added graphene oxide-silicon carbide nanoparticles to present a statistical formulation for the mixture thermal properties." *Physica A: Statistical Mechanics and Its Applications* 521 (2019): 98-112. https://doi.org/10.1016/j.physa.2019.01.035

[18] Mahian, Omid, Lioua Kolsi, Mohammad Amani, Patrice Estellé, Goodarz Ahmadi, Clement Kleinstreuer, Jeffrey S. Marshall *et al.,* "Recent advances in modeling and simulation of nanofluid flows-Part I: Fundamentals and theory." *Physics reports* 790 (2019): 1-48. https://doi.org/10.1016/j.physrep.2018.11.004

[19] Pil Jang, Seok, and Stephen US Choi. "Effects of various parameters on nanofluid thermal conductivity." (2007): 617-623. https://doi.org/10.1115/1.2712475

[20] Keblinski, Phillbot, S. R. Phillpot, S. U. S. Choi, and J. A. Eastman. "Mechanisms of heat flow in suspensions of nano-sized particles (nanofluids)." *International journal of heat and mass transfer* 45, no. 4 (2002): 855-863. https://doi.org/10.1016/S0017-9310(01)00175-2