Chapter 11

Performance Evaluation Criterion of Nanofluid

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Additional information is available at the end of the chapter

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Abstract

In this chapter, we will discuss the increase of heat transfer as well as the increase in pressure drop to determine whether nanofluid is feasible for use in practical applications. Addition of nanoparticles will change the thermal properties of the cooling fluid, by calculation with performance evaluation criterion (PEC). If PEC < 1, then the heat transfer performance is less than the pumping power, so the system is not feasible for use in increasing heat transfer. If PEC = 1, then the heat transfer performance is smaller equal to the pumping power so that the system does not have an impact on increasing heat transfer. If PEC > 1, then the heat transfer performance is higher than the energy used to drive the fluid or pumping power, and then it can be accepted as a solution to the problem of increasing heat transfer, so that the system is feasible for use in practical applications.

Keywords: nanofluid, performance evaluation criterion, heat transfer enhancement, pressure drop

1. Introduction

Today, energy becomes very important in human life; it is used to help human beings activity every day. Without energy, humans will be paralyzed and cannot do anything. Energy savings are a challenging topic to be investigated by scientists. The heat exchanger is a device widely used in the chemical, automotive, electronic, and food industries and involves heat transfer processes that directly influence the economy of these industries. Enhancement of heat transfer is one of the ways used for energy saving. Various methods have been done for the use of energy savings; both are the passive and active methods [1–3]. Passive enhancement methods include a surface coating, rough and finned surfaces, insertion devices, curved geometry, and nanofluid. Active method enhancement needed external energy to maintain the enhancement of the mechanism. Active methods include surface vibration, fluid fibration, electrohydrodynamics (EHD), and the use of the magnetic field. Over the past few decades, the effect of high electric fields on the rate of heat transfer is widely known as electrohydrodynamics (EHD), [4] and the effect of the magnetic field on magnetic iron oxide particle (Fe_3O_4) numerically has been investigated using control volume finite element method (CVFEM) [5]. However, when the available space is limited by the process, it is interesting to use the device with the same size or smaller with better performance. It can be achieved by modifying the cooling with higher thermal conductivity to enhance the heat transfer coefficient when compared with that of conventional fluids for the same geometry.

The objective of this chapter is to how to decrease the size of the thermal system or to increase their transferred thermal power using nanofluid. Nanofluids are colloidal suspensions of nanoparticles which are engineered to have the thermal conductivity higher than that of the base fluid and which can be used for this purpose [6, 7]. However, together with thermal conductivity enhancement, the viscosity is increased, and the gain in transferred heat is paid regarding pumping power. There is a competition between heat transfer rate and pumper power.

2. Nanofluids

The cooling process is the process of heat transfer from a heat source and removed to the environment (heat sink) at the lower temperature. In forced convection heat transfer occurs at high-temperature to low-temperature fluids, which are separated by pipe walls. Increased heat dissipation is done by increasing the convection surface area, i.e., using fins. This method has been abandoned because of the higher the dimensions, and the more massive the equipment consequently the price becomes expensive. The second way is to increase the fluid flow rate, but it will have an impact on the greater use of energy, which causes the system to be inefficient.

The new method to increase heat transfer is to improve thermal properties of fluids especially heat conductivity. This way is by adding solid particles with high thermal conductivity into the cooling fluid with low thermal conductivity as shown in **Figure 1**.

Started by Maxwell as the pioneer [8], adding solid particles of micro size into the fluid is expected to improve thermal properties of fluids, especially heat conductivity. Because the particle size is large enough, the particles quickly agglomerate and cause clogging the channel. Later, Choi [6] introduced the term nanofluid defined as colloids made of a base fluid and nanoparticle size (1–100 nm). The properties of the fluid increase especially the heat conductivity (k), viscosity (μ), and density (ρ) increase in proportion to the increased particle volume concentration, whereas the specific heat (Cp) decreases proportionally to the increase in volume concentration. The effect of nanoparticle concentration on the physical properties of nanofluid has been studied by describing the variation in the ratio of physical properties of nanofluid to pure water as a function of nanoparticle volume concentration [9]. **Figure 2** shows the effect of nanoparticles Al_2O_3 of nanoparticle concentration on the physical properties of nanofluid, i.e., viscosity, density, and thermal conductivity, which have increased, while the specific heat is slightly decreased compared to the base fluid.

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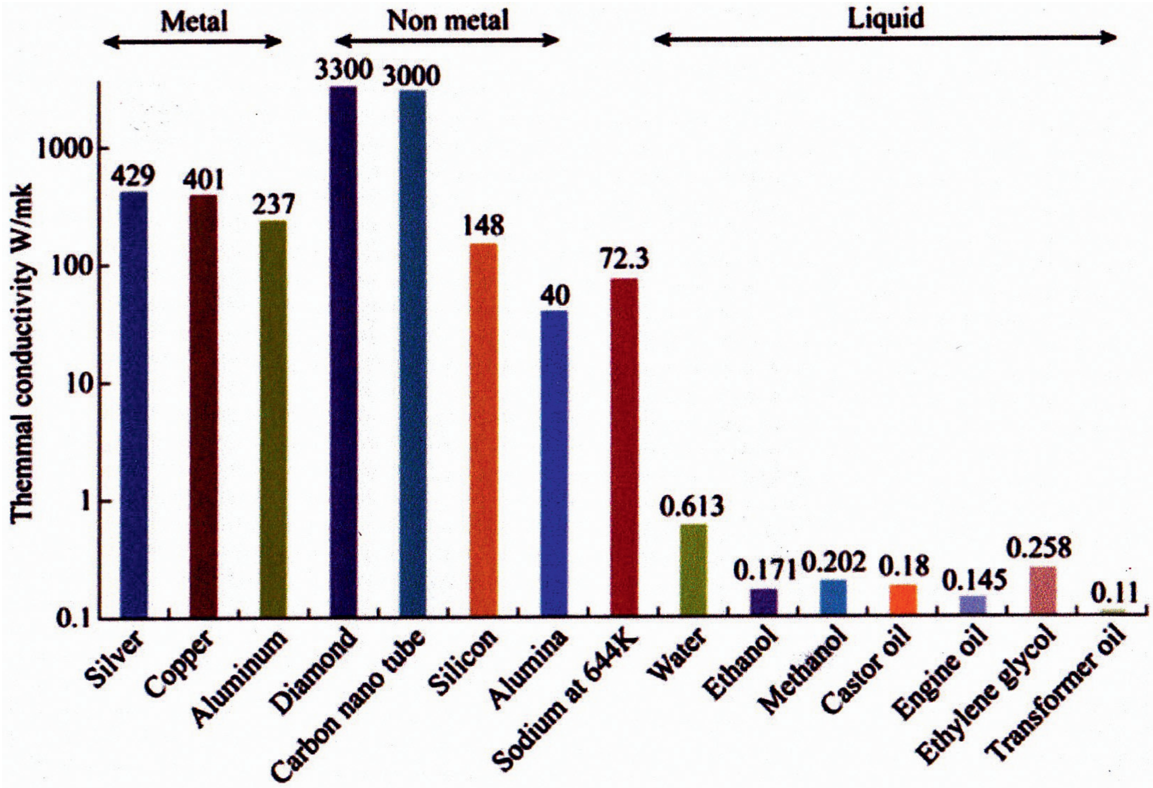

Figure 1. Comparison of thermal conductivity for different materials.

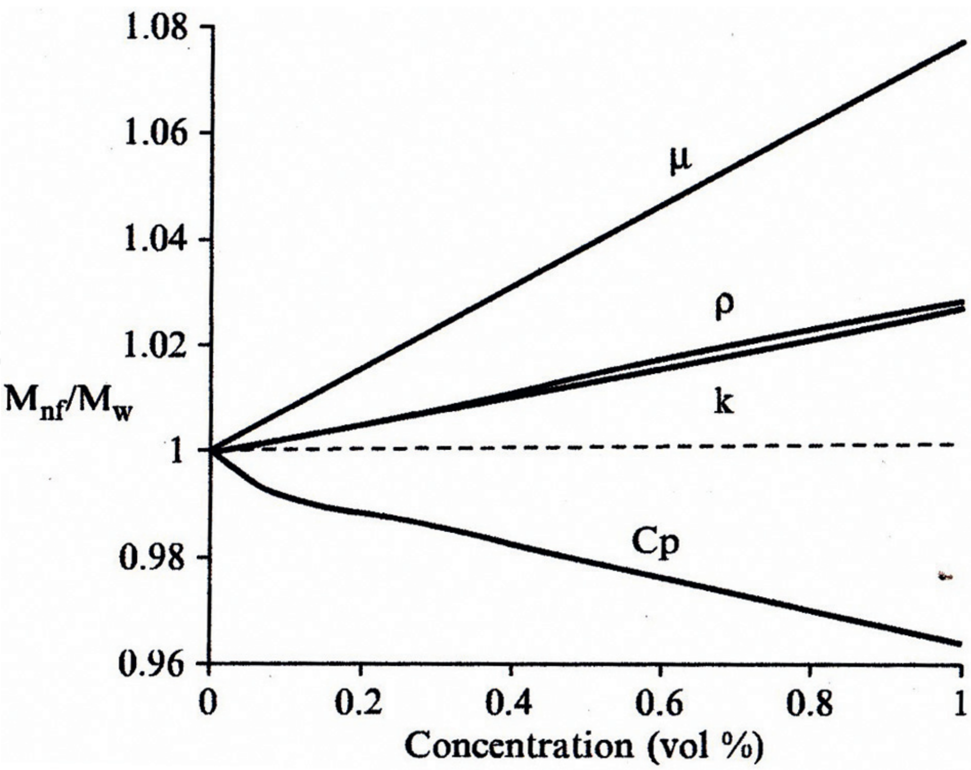

Figure 2. Dimensionless physical properties of nanofluids in comparison to those of pure water.

At first, the researchers only investigated the effect of particle volume concentration on thermal conductivity enhancement. Three possible approaches have been pursuing the study of nanofluid: experimental, empirical, and numerical.

2.1. Preparation methods of nanofluid

For producing high quality of nanofluids, some special conditions are prerequisites, e.g., stable suspension, permanent suspension, no particle agglomeration, and no chemical change of the fluids. Nanofluid preparation is a critical task with the use of nanoparticles for improving the thermal conductivity of base fluid. Fundamentally, there are two methods for producing nanofluids, i.e., (1) two-step method and (2) one-step method.

2.1.1. Two-step method

The two-step method is widely used in producing nanofluid synthesis considering the limitations of nanoparticle supplies commercially by some companies. In this means, nanoparticles are first created and then dispersed in the base fluids. Ultrasonic vibration is used to reduce the agglomeration of particles intensively. Making nanofluids utilizing the two-step processes is challenging because individual particles tend to quickly agglomerate. This agglomeration is due to attractive van der Waals forces between nanoparticles, and the agglomeration is a critical issue in all nanopowder technology, including nanofluid technology, and a crucial step to success in achieving high-performance heat transfer nanofluids [9]. The methods to prevent the agglomeration of particles, usually using a surfactant that regulates acidity (pH) of the base fluids.

2.1.2. One-step method

This method simultaneously generates and disperses the nanoparticles into the fluid base, while the first method deploys previously manufactured nanoparticles into the base fluid. Both methods involve reduction reactions or ion exchange.

Ions and other reactions products are then dispersed in the base fluid together with the nanoparticles since they are almost impossible to separate from their surroundings. For nanofluids containing high thermal conductivity, a one-step method is preferred to prevent particle oxidation. The advantage of a one-step technique is that nanoparticle agglomeration is the minimum, while the disadvantage is that very little nanofluid is produced. The one-step method has produced nanofluids in small quantities for research purposes only, and it is challenging to produce nanofluids commercially by this method [9]. They will be difficult to do for two reasons: firstly, a process that requires a vacuum significantly and slows the production of nanofluid, thereby limiting the production rate, and, secondly, producing nanofluids by this methods is expensive [10].

While most nanofluid productions to date have used one of the above techniques, other techniques are available depending on the particular combination of nanoparticle material and fluids [11]. The early studies on nanofluids focused on the measurement of the thermal conductivity. Later, more experiment regarding the convective heat transfer of nanofluids has been developed continuously.

3. Thermal properties of nanofluid

Thermophysical property, especially the thermal conductivity, is a vital issue in nanofluid heat transfer phenomena. Prediction of thermal conductivity has been a severe challenge until now because many parameters affect the thermal conductivity values. Temperature, type of the base fluid, nanoparticle material, shape, size, volumetric fraction, production, and mixing methods may significantly change the thermal conductivity. The literature research on thermal conductivity of nanofluids is a guide to understand how different parameters affect the value and what kind of thermal conductivity model is selected for the calculation heat transfer enhancement.

Secondly, the viscosity is also crucial in nanofluid heat transfer performance, as the usage of nanofluid viscosity also increases. Prediction of the viscosity of nanofluids is also a challenging topic because of its increase in the pumping power. The similar parameters that affect thermal conductivity affect viscosity value.

3.1. Thermal conductivity of nanofluid

Researchers have widely studied nanofluid thermal conductivity. Investigation the increase of analytical thermal conductivity a solid-liquid mixture by adding solid particles of micro-size balls into a liquid known as the Maxwell model.

$$k_{nf} = \frac{k_p + 2k_b + 2\varphi\left(k_p - k_b\right)}{k_p + 2k_b - \varphi\left(k_p - k_b\right)} k_b \tag{1}$$

where φ is the volume fraction of the nanofluid, k_b is the thermal conductivity of the base fluid, and k_p is the thermal conductivity of the nanoparticles.

Hamilton and Crosser [13] proposed a model for nonspherical particles by introducing a shape factor n given by $n = 3/\varphi$. The thermal conductivity is expressed as follows:

$$k_{nf} = \frac{k_p + (n-1)k_b - (n-1)\varphi\left(k_b - k_p\right)}{k_p + (n-1)k_b - \varphi\left(k_b - k_p\right)} k_b \tag{2}$$

A modified Maxwell's model was proposed by Xuan and Li [14] by considering the Brownian motion of the particles in the base fluid for the thermal conductivity enhancement given as

$$k_{nf} = \frac{k_p + 2k_b + 2\left(k_b - k_p\right)\varphi}{k_p + 2k_b - \left(k_b - k_p\right)\varphi} k_b + \frac{\rho\varphi C_p}{2}\sqrt{\frac{k_B T}{3\pi r_c \mu}} \tag{3}$$

where k_B is the Boltzmann constant, rc is the apparent radius of the cluster, and μ is a dynamic viscosity.

Figure 3 shows the variation of k_{nf}/k_b as a function of alumina volume fraction with and without CTAB along with its best fits with and without interfacial resistance. The k_{nf}/k_b value

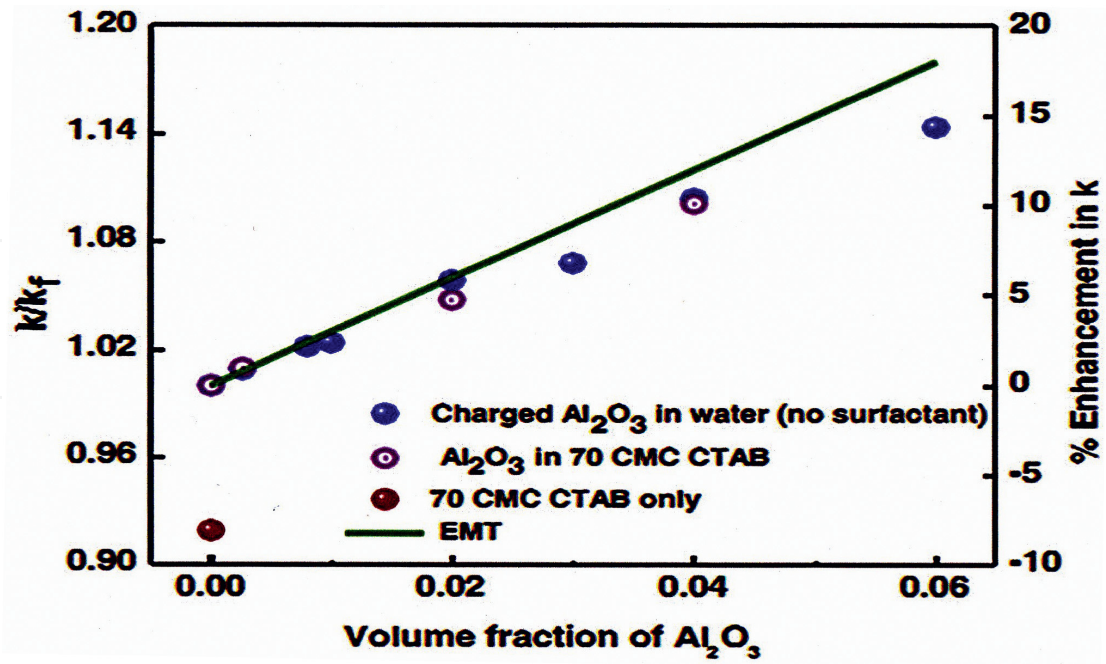

Figure 3. Variation of k_{nf}/k_b as a function of alumina nanoparticle volume fraction with and without CTAB and its best fit with an interfacial resistance.

of 70 CMC surfactant is also shown. The effective medium theory (EMT) fits on the experimental data indicated by the solid line, which shows a perfect agreement with empirical data. It can be seen that the value of knf/kb with pure surfactant was negative, while it was positive at all other concentrations of nanoparticles [15]. In general the higher the particle volume fraction, the higher the nanofluid thermal conductivity of nanofluids.

3.2. Viscosity of nanofluid

Besides the thermal conductivity of the nanofluid, another important thermophysical property is viscosity. Viscosity describes the internal resistance of a fluid to flow, and it is an essential property for all thermal applications involving fluids [10]. In laminar flow, the pressure drop is directly proportional to viscosity. Furthermore, convective heat transfer coefficient is influenced by viscosity. Hence, viscosity is as essential as thermal conductivity in engineering systems involving fluid flow. There has been a lot of research done about nanofluids but mostly related to heat transfer [16]. The increase in viscosity doubled, and energy is required to move the fluid to fourfold so that fluid viscosity plays a significant role in the use of energy in the cooling system.

Most of the viscosity enhancement studies obtained with the dispersion of nanoparticles in the base fluid correlated with the effect of volume fraction, size, and temperature were available in the literature. The rheological behavior of nanofluid categorized into four groups [17, 18], nanofluids with volume concentration less than 0.1 vol.% whose viscosity fits with the Einstein equation, semi-dilute nanofluids with 0.1–5 vol.% with aggregation of nanoparticles,

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semi-concentrated nanofluids with 5–10 vol.% with aggregation of nanoparticles, and concentrated nanofluid with 10 vol.% concentration, is out of the usual nanofluids [19–21].

Theoretical investigations.

There are some existing theoretical formulas to estimate the viscosity of nanofluid. Among them, equation suggested by Einstein [22] is a pioneer in determining the viscosity equation. The assumptions based on the linear viscous fluid containing spherical particles and low particle volume fractions ($\varphi < 0.02$). The suggested formula is as follows:

$$\mu_{nf} = \mu_b(1 + 2.5\varphi) \tag{4}$$

where μ_{nf} is the viscosity of nanofluid, μ_b is the viscosity of the base fluid, and φ is the volume fraction. It is a linear increase of the viscosity with increasing volume concentration. This formula has a limitation that is very small particle concentration. Later on, many researchers contributed to correct this formula [16].

In 1952, Brinkman [23] extended Einstein's formula to be used with moderate particle concentrations, and this correlation has more acceptance among the researchers. For particle concentrations less than 4%, the expression is as follows:

$$\mu_{nf} = \mu_b(1 - \varphi)^{2.5} \tag{5}$$

Considering the effect due to the Brownian motion of particles on the bulk stress of an approximately isotropic suspension of rigid and spherical particles, Batchelor [24] proposed the following formula in 1977:

$$\mu_{nf} = \mu_b\left(1 + 2.5\varphi + 6.5\varphi^2\right) \tag{6}$$

It is clear from the above two relations that, if the second or higher order of φ is ignored, then these formulas will be the same as Einstein's equation has been validated for a particle volume fraction up to $\varphi < 0.1$ [16].

Nguyen et al. [17] showed that both the Brinkman [23] and Batchelor [24] equations severely underestimate nanofluid viscosities, except at very low particle volume fractions (lower than 1%). They have proposed two correlations for nanofluids consisting 47 and 36 nm of Al_2O_3 nanoparticles with water, respectively, as follows:

$$\mu_{nf} = \mu_b \times 0.904e^{0,1842\varphi} \tag{7}$$

$$\mu_{nf} = \mu_b\left(1 + 0.025\varphi + 0.015\varphi^2\right) \tag{8}$$

Both of these models determine the viscosity by only considering base fluid viscosity and the particle volume fraction. Furthermore, they proposed a correlation for computing CuO water viscosity as shown in Eq. (9) [16]:

$$\mu_{nf} = \mu_b\left(1.475 - 0.319\varphi + 0.051\varphi^2 + 0.009\varphi^3\right) \tag{9}$$

Most of the equations have been developed to express viscosity as a function of volume fraction of nanoparticles. However, the temperature is an important factor in nanofluid viscosity, and, consequently, several equations have been created to investigate the temperature effect on viscosity. Some literature is available about the temperature effect over nanofluid viscosity [16]. Yang et al. [25] experimentally measured temperature effect of viscosity with four temperatures (35, 43, 50, and 70°C) for four nanofluid solutions taking graphite as nanoparticles. They experimentally showed that kinematic nanofluid viscosity decreases with the increase of temperature. Anoop et al. [26] studied the viscosity of CuO-ethylene glycol, Al_2O_3-ethylene glycol, and Al_2O_3-water for the temperature range of 20–50°C with a volume concentration of 0.5, 1, 2, 4, and 6 vol.%. They found that viscosity reduces with an increase in temperature. Investigation studies by Duangthongsuk and Wongwises [27] with TiO_2 and water for a temperature range of 15–50°C have found that viscosity of nanofluids decreases with the rise in temperatures.

A correlation between viscosity and temperature for pure fluids was presented by Reid et al. [28]:

$$\mu_{nf} = A\exp\left(\frac{B}{T}\right) \tag{10}$$

where A and B are the functions of concentrations and T is temperature that is written by Yaws [29] as

$$\overset{\mu}{\log\,(nf)} = A + BT^{-1} + CT + DT^2 \tag{11}$$

where A, B, C, and D are the fitting parameters.

Some correlations have also been suggested taking into account both temperature and volume fraction effects on viscosity [16]. In 2006, Kulkarni et al. [30] proposed correlations that relate viscosity of copper oxide nanoparticles suspended in water with a temperature range of 5–50°C:

$$\ln\mu_{nf} = A\left(\frac{1}{T}\right) - B \tag{12}$$

here, A and B are functions of volume fraction φ. This correlation is mainly for aqueous solution and is not applicable to nanofluids in the subzero temperature range.

The application for nanofluid with low viscosity (high temperature) and high thermal conductivity (small volume fraction) is promising for the future.

4. Heat transfer enhancement

Enhancement of heat transfer is a favorite and an important topic that is highly relevant to current and future energy systems and renewable energy systems as well as for energy conservation and environmental protection. The increase in heat transfer statement is usually expressed by increasing the heat transfer coefficient of a system. The purposes of improving the heat transfer rate are to reduce the size and simultaneously increase the capacity of the thermal system.

The thermal system is expressed by thermal performance, which is the increase of heat transfer coefficient (h) and hydraulic performance, that is, the amount of energy required to circulate fluid within the system. The thermohydraulic performance is used as the performance indicator of heat exchange tool. The heat exchanger performance test means comparing the characteristics of the heat transfer coefficient and pressure loss (pressure drop) on a device of the same dimension.

Heat transfer enhancement is the process of increasing the effectiveness of heat exchanger. It can be achieved when the heat transfer power of a given device increased or when the pressure losses generated by the device are reduced.

5. Performance evaluation criteria (PEC)

The main advantage of the nanofluid is it has a high thermal conductivity, which is used for improving the efficiency of the thermal system. Adding small particles to the base fluid liquid increases the viscosity of nanofluid [31], which also increases the pressure drop on the systems. Due to the increased pressure drop, the operational costs of a system will be high due to the increase in pumping power. Hence, the viscosity of nanofluid is a significant parameter for determining the feasibility of nanofluid for heat transfer applications, depending on the significant increase in both thermophysical-properties of thermal conductivity and increased viscosity [19].

As heat transfer and pressure drop are the most critical factors, they can be compared to several approaches. It is defined as the ratio of heat transferred to the required pumping power in the test section. To evaluate the benefits provided by the enhanced properties of the nanofluids studied, an energetic performance evaluation criterion (PEC) is defined as heat transfer and hydrodynamics are the most critical factors. They can be compared to a global energy approach using the PEC defined as the ratio of heat flow rate transferred to the required pumping power in the system [32]:

$$PEC = \frac{mC_p(T_i - T_o)}{v\Delta P} \tag{13}$$

5.1. Pressure drop

Additionally, the heat transfer rate of nanofluids increased due to increased thermal conductivity, and the pressure drop also increased due to the increase in the nanofluid viscosity.

The pressure drop ($\Delta p = p_1 - p_2$) is directly related to the pumping power to maintain flow; for laminar flow the pressure drop is shown in Eq. (14):

$$\Delta p = \frac{32\mu L V_{avg}}{D^2} \tag{14}$$

The pressure drop due to viscous effects represents an irreversible pressure loss, and it is called pressure loss Δp_L in circular tube that can be determined from the pressure drop using the Darcy-Weisbach equation below:

$$\Delta p_L = f \frac{L}{D} \frac{\rho U^2}{2} \tag{15}$$

But mass flow rate is $\acute{m} = \rho A U$, and the pressure drop from Eq. (15) is

$$\Delta p = f \frac{L}{D} \frac{\rho \left(\frac{\acute{m}}{AU}\right)^2}{2} = f \frac{L}{D} \frac{4\acute{m}\rho}{\pi D^2} = f \frac{L}{D^3} \frac{4\acute{m}\rho}{\pi} \tag{16}$$

Performance evaluation criteria by Lee [33] obtained a boundary line for laminar flow using thermal conductivity and viscosity of nanofluids to compared than base fluid. The method has been used to analyze the performance of nanofluid in a microchannel heat sink. A microchannel heat sink as a passive method can be a cooling device by dissipating heat into the surrounding air. The microchannel heat sink consists of N number of circular channels, each with diameter d, as shown in **Figure 4**. The total channel width W is constant ($W = N \times d$).

Assume a constant heat flux boundary condition for all channel, and the flow is hydrodynamically and thermally fully developed. The heat transfer flow rate for convection heat transfer as Newton's law of cooling is

$$Q = hA\Delta T \tag{17}$$

The difference in temperature between the surface wall temperature and the local bulk fluid temperature is

$$Q = T_w - T_m = \frac{Q}{N\pi dLh} = \frac{Q}{\left(\frac{w}{d}\right) dL} \frac{1}{kNu} \tag{18}$$

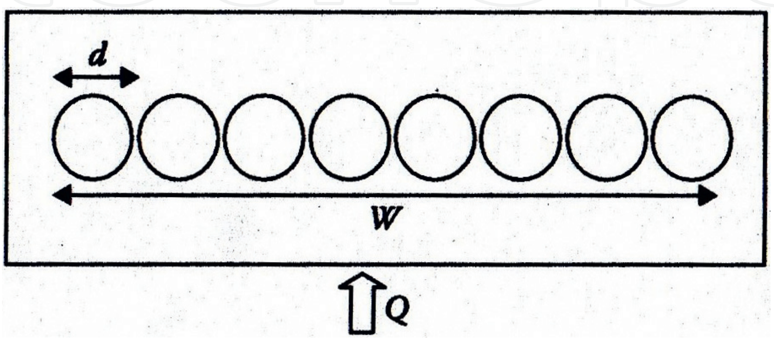

Figure 4. A schematic of a microchannel heat sink.

The pressure drop for a channel with length L as follows:

$$\Delta P = f\frac{L\rho U^2}{2d} \tag{19}$$

For laminar flow, $f = 64/\Re$

$$\Delta P = \frac{128\mu\left(\frac{V}{N}\right)L}{\pi d^4} = \frac{128\mu VL}{\pi W d^3} \tag{20}$$

The above equation can be written to d as follows:

$$d = \left(\frac{128\mu VL}{\pi W\Delta P}\right)^{1/3} \tag{21}$$

Therefore, at a fixed volume flow rate, fixed pumping power, and a given channel length, the following correlation can be obtained for laminar flow with constant a Nusselt number:

$$\Delta T = \frac{Q}{W\pi LNu}\left(\frac{128\mu VL}{W\pi\Delta P}\right)^{1/3} \infty \frac{\mu^{\frac{1}{3}}}{k} \tag{22}$$

If the nanofluid is more efficient than their base fluids, the difference between the wall and bulk fluid temperature should be smaller than the temperature using base fluids:

$$\Delta T_{bf} > \Delta T_{nf} \tag{23}$$

and

$$\frac{k_{nf}}{k_{bf}} > \left(\frac{\mu_{nf}}{\mu_{bf}}\right)^{1/3} \tag{24}$$

Eq. (24) shows that nanofluids are effective as long as the thermal conductivity enhancement is more than the one-third power of the viscosity enhancement for laminar flow regime. The boundary line for the performance of nanofluids in laminar flow regime is shown in **Figure 5a**. The thermal conductivity and viscosity ratios of Al_2O_3 and multiwalled carbon nanotube (MWCNT) nanofluids are measured in the work of Wu et al. [34] plotted in **Figure 5**. Alumina nanofluids can provide better performance than base fluids under laminar flow regime, whereas the tested MWCNT nanofluids are very unfavorable.

If a ratio nanofluid viscosity to the base fluid $\frac{\mu_{nf}}{\mu_{bf}}$ is equal to two, the ratio thermal conductivity of nanofluid to thermal conductivity base fluids must be more than 1259 as shown in **Figure 4a**.

Figure 6 shows the optimization of the preparation of nanofluid, starting with the measurement of the stability of nanofluid, if it fast agglomerates necessary additional treatment, for high stability by adding surfactant or surface modifier.

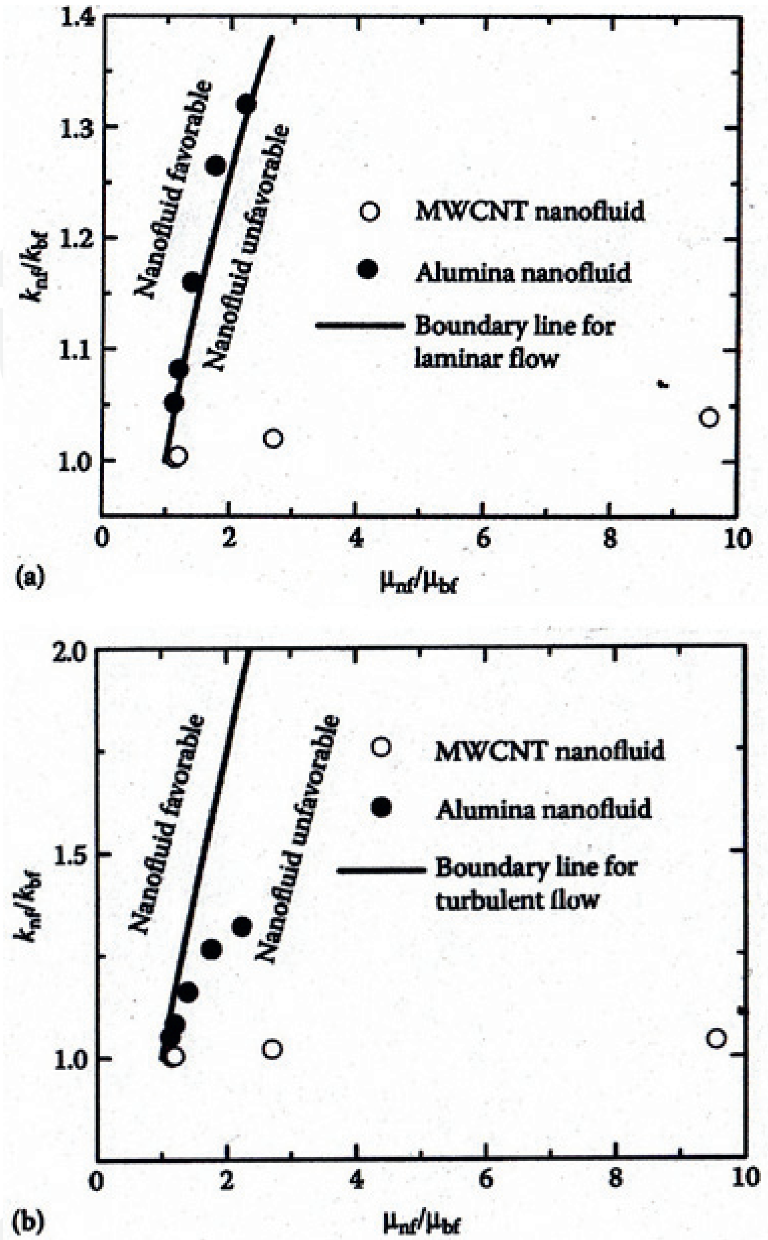

Figure 5. The boundary line for the performance of nanofluid at fixed volume flow rate and fixed pumping power: (a) laminar flow regime and (b) turbulent flow regime. The alumina and MWCNT nanofluids measured in Wu et al. correlation [32].

Viscosity measurements were performed to determine the viscosity value of nanofluid, for high viscosity nanofluid required special treatment to decrease viscosity, i.e., nanofluid used at the temperature above room temperature. Following the above discussion with an increasing temperature, the viscosity of nanofluid decreases.

When the viscosity of the nanofluid is low, and the thermal conductivity of the nanofluid is high, nanofluids can be used in practical applications.

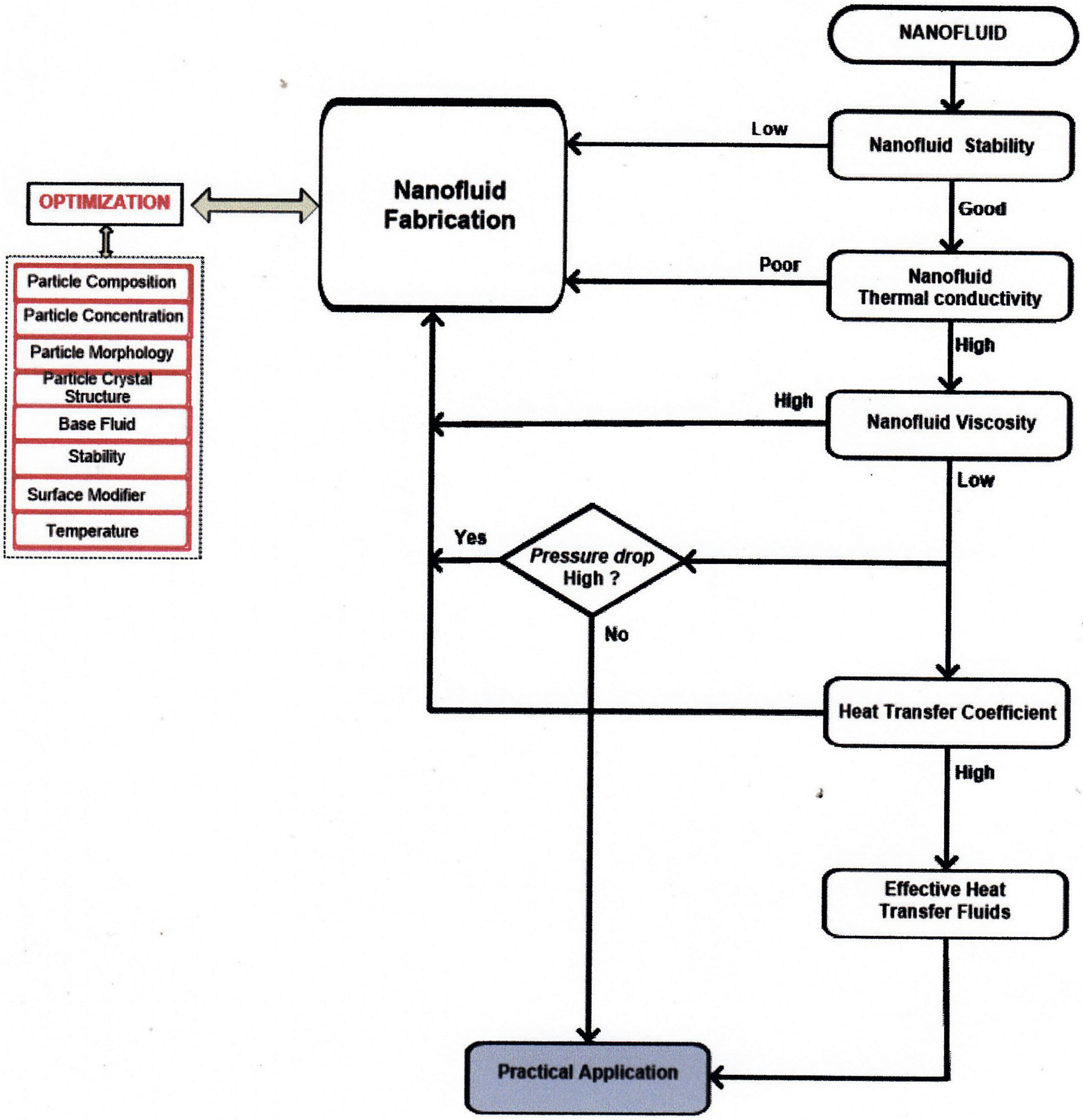

Figure 6. Optimization fabrication of nanofluid.

6. Conclusion

The above discussion can be concluded that the application for nanofluid with low viscosity (high temperature) and high thermal conductivity (small volume fraction) is promising for the future.

Nanofluid can be used as a fluid that has a high-performance increase of heat transfer suitable only for the cooling process, as hot fluids with low particle volume fraction.

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