

COOLING PERFORMANCE INVESTIGATION OF NANOFLUIDS FOR INTERNAL COMBUSTION ENGINE SYSTEMS

by

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ABSTRACT

COOLING PERFORMANCE INVESTIGATION OF NANOFLUIDS FOR INTERNAL COMBUSTION ENGINE SYSTEMS

This study aims to evaluate numerically the cooling performance increase of an internal combustion engine cooling system due to the use of nanofluids. Throughout the study a set of analyses has been done to determine the performance enhancement due to addition of nanoparticles; and the performance enhancement for two nanoparticle materials, alumina and hexagonal boron nitride (hBN) is compared. First, numerical model verification is done for diamond and TiO_2 containing nanofluids, comparing the model results with experimental results. Then an uncommon material in nanofluid literature, hexagonal boron nitride is introduced and its thermal performance is investigated in a horizontal tube and in turbulent regime. As a final analysis, a car radiator flow channel is modeled numerically to investigate the cooling performance of nanofluids. Water and ethylene glycol (EG) mixture (50% - 50%) is chosen as base fluid for the radiator analysis, in which the effects of two nanoparticle materials, alumina and hexagonal boron nitride in various particle volumetric concentrations up to 5% are evaluated and compared. Thermal performance increase, in terms of radiator cooling capacity increase is evaluated with respect to particle volumetric concentration, air side convection and radiator frontal area. As a result, it is shown that hexagonal boron nitride containing nanofluids have superior thermal performance with respect to alumina containing ones. However, the results indicate limited thermal performance improvement for the investigated cooling system by the use of nanofluids in general.

ÖZET

NANOAKIŞKANLARIN İÇTEN YANMALI MOTOR SOĞUTMA SİSTEMİ SOĞUTMA PERFORMANSLARININ İNCELENMESİ

Bu çalışmada içten yanmalı motor soğutma sistemlerinin nanoakışkan kullanımı sayesinde soğutma performansı artışlarını nümerik olarak incelenmesi hedeflenmiştir. Çalışma boyunca nanopartiküller sebebiyle oluşan performans artışını gözlemlemek üzere çeşitli analizler yapılmış ve iki nanopartikül materyali olan alüminyum oksit ve hegzagonal bor nitritin sağlamış olduğu performans artışları karşılaştırılmıştır. İlk olarak elmas ve TiO_2 içeren nanoakışkanlar için yapılan analiz sonuçları literatürdeki deneysel sonuçlarla karşılaştırılarak nümerik modellemenin doğrulaması yapılmıştır. Daha sonra ise nanoakışkan literatüründe sık kullanılmayan bir madde olan hegzagonal bor nitriti için yatay silindirde, sabit ısı akısı sınır şartıyla ve türbülanslı akış analizi yapılarak genel performansı incelenmiştir. Son olarak bir araba radyatörü kanalı modellenerek nanoakışkanların soğutma performansı araştırılmıştır. Bu analizlerde nanoakışkan için baz sıvı olarak su ve etilen glikol (%50 - %50) karışımı seçilmiş ve bu nanoakışkanda %5'e varan farklı konsantrasyonlardaki alüminyum oksit ve hegzagonal bor nitrit nanoparçacıkların etkisi karşılaştırılmıştır. Parçacık konsantrasyonuna, hava konveksiyonuna ve radyatör ön alanına bağlı olarak termal performans artışı gözlemlenmiştir. Sonuç olarak hegzagonal bor nitriti içeren akışkanların alüminyum oksit içerenlere göre çok daha iyi performans artışı sağladıkları, ancak genel olarak nanoakışkan kullanımının incelenen sistem için performansta çok kısıtlı bir artış sağlayabildiği gözlemlenmiştir.

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LIST OF SYMBOLS

A	Area
A_b	Base area
$A_{cr,t}$	Total radiator frontal area
$A_{cr,c}$	Total air channel cross-sectional area
A_f	Fin area
C_a	Heat capacity of air
C_w	Heat capacity of liquid
C_r	Heat capacity ratio
$c_{p,b}$	Specific heat capacity of base fluid
$c_{p,m}$	Effective specific heat capacity of nanofluid
$c_{p,p}$	Specific heat capacity of nanoparticle material
D_h	Hydraulic Diameter
F	Logarithmic mean temperature difference correction factor
f	Friction factor
h	Heat transfer coefficient
h_a	Heat transfer coefficient of air
h_w	Heat transfer coefficient of liquid
k_b	Thermal conductivity of base fluid
k_m	Mean thermal conductivity of the fluid
k_p	Thermal conductivity of nanoparticle
k_{pe}	Effective thermal conductivity
N_f	Number of fins
NTU	Number of Transfer Units

Nu	Nusselt number
p	Pressure
Q	Heat load
Re	Reynolds number
$T_{a,i}$	Air inlet temperature
$T_{a,o}$	Air outlet temperature
T_b	Bulk temperature
T_s	Surface temperature
$T_{w,i}$	Liquid inlet temperature
$T_{w,o}$	Liquid outlet temperature
ΔT_{lm}	Logarithmic mean temperature difference
t_{tube}	Tube thickness
UA	Overall heat transfer coefficient
v	velocity
$v_{a,a}$	Approach velocity of air
$v_{a,c}$	Air velocity in channel flow
$\dot{V}$	Volumetric flow rate
γ	Ratio of nanolayer thermal conductivity to the particle thermal conductivity
ε	Effectiveness
η_0	Overall fin efficiency
η_f	Fin efficiency
μ_b	Base fluid viscosity
μ_m	Effective viscosity of the nanofluid

ρ_b	Base fluid density
ρ_m	Density of the nanofluid
ρ_p	Nanoparticle density
σ	Ratio of nanolayer thickness to nanoparticle diameter
φ	Additional cooling load enhancement
$\varnothing$	Particle volumetric concentration in nanofluid

LIST OF ACRONYMS / ABBREVIATIONS

BN	Boron nitride
CNT	Carbon nanotube
EG	Ethylene Glycol
hBN	Hexagonal boron nitride
NTU- ϵ	Number of Transfer Units - Effectives Method
SANSS	Submerged Arc Nanoparticle Synthesis System
VEROS	Vacuum Evaporation onto a Running Oil Substrate

1. INTRODUCTION

1.1. Thesis Motivation

Heat transfer plays an important role in engineering applications for many different areas. With the current speed of development in science, technology and engineering as well as the competition in scientific and industrial world, heat transfer improvements continues to attract the attention of the scientists, researchers and industrial companies. Automotive industry, computers and electronics, power plants and reactors, heating, ventilating and air conditioning systems, food industry, medical industry and sensitive measurement techniques are common examples of the most important industries, in which heat transfer has a key role in terms of cooling or obtaining thermal stability. Therefore, new methods to increase heat transfer are investigated continuously.

Common use of heat transfer applications in various industries led to a large variety in these applications. Several control parameters such as required amount of heat transfer, boundary conditions, geometrical considerations, environmental factors and applied heat transfer methods vary from process to process. For mechanical designs, it is important that the parts in motion, friction or under pressure are able to be cooled down efficiently to maintain their low temperature properties in order to prevent failures due to changed properties caused by heat generation. In chemical processes, heat transfer and control is needed to start a process, or obtain the required thermal conditions for an efficient chemical process. In electronics, the temperature of the chips has to stay under a certain limit, so that the chip can work properly. In power generation, the power generation units in power plants have to be in a certain interval of temperature range for an efficient and safe process. In food industry, heat transfer is used to provide constant temperature in order to keep the food fresh. As the number of examples can be augmented, the examples shown so far are enough to prove the importance of heat transfer.

Due to the improvements in the science and technology, as well as the needs of society and optimization of current applications; the importance of heat transfer efficiency increased significantly for new generation designs and developments. Since in most

designs the efficiency of other factors have been maximized, that the limiting factor for the efficiency of most systems is the quality and thermal performance related properties of the heat transfer fluid. Therefore, the focus has been set on the heat transfer fluids to increase the heat transfer efficiency.

As one of the largest industries, automotive industry is a well known supporter of research and development in a global aspect. Several factors such as fierce and stiff competition, customer comfort and needs, laws and regulations, and seeking for more profitable solutions lead to constant search for development and refinement. Therefore, every small case of advantage is considered crucial. Vehicle engines, being most advanced, complex and important part of commercial and passenger vehicles are especially in focus of research and development departments. One major goal in internal combustion engine development is accepted as improving current cooling systems and achieving necessary cooling requirements with smaller and lighter cooling systems. The primary objective on this branch is to enhance the amount of cooling load for cooling systems in order to increase heat removal from the engine. Therefore, the limits for engine working conditions will also be increased. The availability of higher heat removal can influence systems in two ways: improvement in performance with the same system or achieving the same performance with smaller and more compact systems.

Today, a trend in automotive companies can be observed as continuously working on increasing the performance of engine cooling systems. In order to do that, three general methods have been evaluated: changing flow geometry, changing boundary conditions and enhancing thermal conductivity. Due to the limitations of the product size and geometry, as well as the flow conditions, changing the flow geometry is not a preferred option in most applications. The efficiency increase due to the size and geometry change is analyzed and optimized in most products, and the limit on that method has been reached. The second method, the adjustment of boundary conditions, is also an option with very limited freedom due to the conditions of the related heat transfer application. The boundary conditions may be influenced in relatively small amounts; however, in general they are limited due to the environmental factors as well as heat transfer conditions. In most industries the contribution of the first two methods to the heat transfer enhancement has been maximized, and further increase is only possible by the third option; change in

thermal characteristics of the heat transfer fluid. Therefore, searching for heat transfer media with higher thermal performance has become a primary aim for further heat transfer enhancement development.

Besides a great number of other industries in the world, the automotive industry also shares the common need for better heat transfer fluids for further development, and the possibility for more efficient cooling is therefore anticipated with enthusiasm. The focus of the studies on this subject is concentrated on the heat transfer fluid characteristics. Despite the high thermal conductivity of common heat transfer fluids with respect to other fluids, these fluids have relatively low thermal conductivity with respect to most solids [1]. This fact gave the idea of mixing solid particles into the fluid for better thermal conductivity. However, agglomeration and sedimentation of the solid particles created a more significant problem, since the sedimentation disrupts the uniformity of the fluid properties, reduces the effect of the particles and more importantly causes congestion in the pipes and channels and blocks fluid flow. These difficulties led to the idea of decreasing the particle sizes to minimize the effect of gravity, so that the sedimentation also minimizes. The advantage of better internal combustion engine coolants can serve the automotive industry for two ways: they may increase the amount of cooling in current systems and therefore improve the engine performance, or they may also provide the same amount of cooling with systems of smaller size and therefore weight and cost reduction as well as more freedom in design parameters is obtained. Recently few studies investigating the nanofluids as internal combustion engine coolants have been published and can be found in literature. As being one of the important potential applications of nanofluids, an increase in the publications on this subject is expected in the near future.

During the research for better heat transfer fluids, nanofluids have shown themselves a significantly valuable candidate to investigate with their performance so far [2-4]. Despite some concerns for their stability related problems, nanofluids show very good heat transfer characteristics in recent studies. Besides showing a towering thermal conductivity enhancement, they also provide better convectional effects. Nanofluids also have better stability and lower viscosity with respect to other suspensions [4], which makes them more favorable to be evaluated as a replacement to current heat transfer fluids. Considering these results, the rapid increase of interest on the topic of nanofluids over the last decade was not

unexpected, and as a result they are considered as the primary candidate to be the next generation heat transfer fluids.

Despite the high motivation and interest on nanofluids, the topic is still not fully investigated due to the limited time since their development, extensive content and lack of technical developments. Therefore, the topic still needs more attendance to be understood completely. In conclusion, considering the industrial requirements of new heat transfer fluids as well as promising results of nanofluids, the topic of “nanofluids” gives a good opportunity to step forward for an original and valuable research subject.

Under the enlightenment of this knowledge, the application of nanofluids for automobile engines is recently taken into consideration. Today, few researchers are working on the topic to investigate the possibility for developing this new generation coolants for automotive engines, and more researchers are inspired by the topic on a daily basis.

1.2. Nanofluids as a Potential Solution

Nanofluids are a relatively new topic in fluid mechanics and heat transfer, having been discovered in 1993 by S.U.S. Choi [2, 4]. However, with the promising results of preliminary research, the topic drew worldwide attention quickly. Nanofluids are colloidal suspensions consisting of a base fluid and small sized particles evenly distributed in the fluid. The difference of nanofluids from classical colloidal suspensions is the extremely small size of their particles. The average size of the particles varies due to several factors such as the production method, particle material or particle tendency to clustering [5]. The particle materials with higher thermal conductivity with respect to the base fluid are chosen to increase the thermal performance of the whole suspension. Due to the small size of the particles, nanofluids show significantly better characteristics such as extreme thermal performance enhancement and better stability with respect to other suspensions, which give them advantages in favor of being the suitable and preferable choice for the heat transfer applications [6].

1.3. Boron Nitride

Boron nitride is a well known and easily acquirable synthetic chemical compound, that exists in three different crystalline forms. Most stable and most common form of boron nitride is hexagonal form, in which the molecules are ordered in a layered structure. Cubic boron nitride consists of molecules in cube (sphalerite) structure, and the third type wurtzite boron nitride, and is an extremely rare form, which cannot be produced in large amounts for practical use.

Boron nitride is widely used in mechanical applications [7, 8] due to its excellent thermal and chemical stability and low obtaining cost. Moreover, boron nitride is usually used as material for high temperature equipment. Cubic boron nitride has higher thermal conductivity with respect to hexagonal boron nitride, which makes it more favorable in thermal applications. However, production of cubic boron nitride nanoparticles smaller than 100 nm is commercially unavailable up to date, whereas hexagonal boron nitride is available in nanoparticle form. Therefore, hexagonal boron nitride is chosen as the material in focus of this study. One important property of hexagonal boron nitride is directional thermal conductivity. Due to the layered hexagonal structure, hexagonal boron nitride has different thermal conductivities in different axial directions. The thermal conductivity along the layers is extremely higher than thermal conductivity across the layers.

As a final fact, rich boron mines in Turkey provide a good availability of boron, which can be used as boron nitride nanoparticle production, and the possibility of commercial use in coolant nanofluids may add one more industrial need for boron, increasing its value in global market.

Good thermal characteristics of boron nitride allow it to be a promising candidate for the use in nanofluids. Besides hexagonal boron nitride is commercially available in nanoparticle form today. Therefore, it will be introduced and investigated for this purpose in this study.

1.4. Outline of the Study

In this study, the possibility of using nanofluids as coolants in internal combustion engine systems will be investigated. Nanofluids with various nanoparticle concentrations will be analyzed numerically for their cooling performance. Besides common nanoparticle materials such as alumina, hexagonal boron nitride nanoparticles will be introduced, and their performance enhancement will be compared.

As the first step to investigate the nanofluids, a comprehensive literature survey covering the general knowledge and worldwide studies on the subject is carried out. This review, presented in Chapter 2, provides detailed information and scientific conclusions about the topic. Detailed definition of nanofluids is given, studies and research subjects on nanofluids have been covered, and the results and conclusions have been clarified. This chapter gives a clear view of today's achievements and future aims in the research area of nanofluids.

Chapter 3 provides validation and verification of the numerical method, in cylindrical tube, repeating various experimental results in literature numerically and comparing the results with experimental data. This chapter is essential in terms of proving the validity of the study, and introducing the details of the modeling used in the study.

General thermal performance and behavior of hexagonal boron nitride containing nanofluids is introduced in Chapter 4 in order to simulate the effects of hexagonal boron nitride. Hexagonal boron nitride – water nanofluid is examined in this chapter for cylindrical tube turbulent flow, and general thermal performance characteristics are evaluated. This chapter is an important step to fulfill the general performance expectations from hexagonal boron nitride containing nanofluids, since they are not common and well investigated nanofluids in literature.

Engine cooling system analysis is completed in Chapter 5, where a radiator tube is modeled and analyzed numerically. In this chapter alumina and hexagonal boron nitride are chosen as nanoparticle materials to be investigated. Nanofluids containing these nanoparticle types separately in various volumetric concentrations in a 50% - 50% mixture

of water and ethylene glycol base fluid are subjected to a variety of boundary conditions, and the results are compared with each other. General performance increase is examined and the effects of particle material are underlined by comparing the results for hBN and Al_2O_3 containing nanofluids.

Chapter 6 is the conclusion part of the study. It consists of a short summary of the results, interpretation of those results, comments, and suggestions for future work.

2. LITERATURE REVIEW

2.1. General Knowledge about Nanofluids

2.1.1. Definition

As specified before in the Chapter 2, nanofluids are colloidal suspensions consisting of a base fluid and particles flowing in the base fluid. The size and shape of the particles change from one suspension to another. Although there exist a few studies and released articles with nanofluids with particle diameter up to 150-200 nanometers, as a general opinion the average particle diameter must not exceed 100 nanometers for a suspension to be accepted as nanofluid. The shape of the particles may differ due to the production method, particle material and several other factors. In numerical simulations it is common to assume the particles as spherical due to simplicity.

A large variety of materials and combinations are available in literature to be used as nanofluids. Base fluids for nanofluids are generally chosen as water, ethylene glycol, oils or engine coolants. In various cases the compounds of these fluids at several ratios are also used as the base fluid. Typical materials chosen nanoparticles are metals, oxides, carbides and carbon nanotubes [9]. Most studies use alumina, copper oxide and titanium dioxide for the nanoparticle material. However, nanofluids containing nanoparticles with other materials such as copper, gold, diamond, silver, iron, silicon carbide, carbon compounds and magnetite are also common. The criteria to select the base fluid are the same as the common heat transfer fluids. The material of the particles is chosen considering the thermal conductivity of the particle, availability of the particle in terms of production and cost, and the inertness of the material.

Due to their high thermal performance enhancement, nanofluids are mainly proposed as next generation heat transfer fluids. Therefore, the studies on nanofluids are generally concentrated on the heat transfer problems and heat transfer performance. Besides the topic of thermal performance evaluation of nanofluids, the research extended to the other

properties of nanofluids. A vast number research articles about their rheological properties, production methods and stability evaluation are published and available in the literature.

2.1.2. Historical Development

Despite the recent discovery of nanofluids, the concept of using colloidal suspensions to enhance heat transfer has attracted the scientists for a longer period of time. One of the earliest works known is Michael Faraday's work on gold particles in 1857, described in several studies [1, 6]. In 1881, Maxwell also tried to enhance thermal properties of fluids by adding particles in it [2, 10]. However, the sizes of the particles were not small enough to be considered as nanoparticles. Due to the technical limitations, the particle size was on the millimeter scale, and due to stability related problems caused by large scale of particle diameter, the results have shown inefficiency. Maxwell observed abrasion of the surface, clogging of channels, eroding of the pipeline and dramatic increase of the pressure. These problems limited the practical applications, and the colloidal suspension solution remained as a theoretical solution to the heat transfer problem. During the time period until 1980's, colloidal suspensions were investigated several times in terms of their potential as heat transfer fluids. However, due to large particle size, agglomeration and sedimentation problems were observed. These problems caused ineffective results for the potential.

The downscaling of heat transfer problems into smaller sizes started in 1981 [4], when D.B. Tuckerman introduced the microchannel technology; which can be summarized as using close proximity micro sized channels in heat exchangers for more efficient heat transfer, limited pressure drop and higher performance. The success of the microchannel design brought investments into micro-scaled heat transfer problems. After the success in geometrical aspect of the heat transfer, in 1985 Argonne National Laboratory started the program to develop advanced fluids to replace heat transfer fluids [4]. In 1993, S.U.S. Choi proposed nanofluids to the literature [4]. Two years later, in 1995 the first seminal paper on the concept of nanofluids was published by Choi at the American Society of Mechanical Engineers Winter Annual Meeting. In 1999 the article on thermal conductivity enhancement of nanofluids, published by Choi and his coworkers drew the attention of scientific world to the subject [11]. From 2000 to present nanofluids became a deeply

investigated topic, and the number of research articles and theses on the topic increased dramatically. In 2007 the first single theme conference on nanofluids, “Nanofluids: Fundamentals and Applications” was held in Copper Mountain, and the first book with the single theme of nanofluids; “Nanofluids: Science and Technology” [12] is published.

2.1.3. Nanofluid Availability

This part will introduce the basic knowledge about the production methods of nanofluids. The detailed information on the production methods and the studies done so far on that topic will be introduced in Section 2.2.

Nanofluid production is possible by various methods in literature. Besides the effectiveness of the method, the production method is also an important parameter for performance characteristics of nanofluids, since it does affect directly the properties and the quality of the nanofluid, as well as its production costs. Therefore, the topic of production methods is an active and important topic of investigation for the nanofluids.

The production methods of the nanofluids affect their properties substantially. The most important characteristic to be changed is the stability of the nanofluid. Despite similar materials, conditions, properties and environmental factors, nanofluids produced by different methods show different characteristics [9]. Detailed information about this topic can be found in Section 2.2.

Today, common nanoparticles and nanofluids are commercially available. However, mass production of nanofluids for commercial use and practical applications is still an achievement to be reached. Moreover, continuous effort on the development of new nanofluids and nanofluid production methods can be observed through the studies in literature. Development of new methods to ensure easier and less expensive production, and providing the availability of new nanofluid types is accepted as one of the favorite challenges in literature. Therefore, the knowledge on production methods extends continuously.

2.1.4. Research Subjects for Nanofluids

As emphasized before in Chapter 1, the main reason behind the interest on nanofluids is their extraordinary results in heat transfer enhancement and improved colloidal stability. Due to these increased thermal properties and high stability with respect to classical colloidal suspensions, nanofluids are studied for their potential to be the next generation heat transfer fluids. Therefore, the research on the nanofluids is focused on their thermal performance enhancement in order to use them in practical applications of heat transfer problems. However, the research is not limited by merely the thermal performance. For the consideration of heat transfer fluids, other properties including the stability, viscosity properties, production methods and theoretical reasoning also possess great importance.

The research on nanofluids can be classified in five main topics: the determination of methods to produce nanofluids, the experimental work to determine the fundamental characteristics of nanofluids, experimental work to determine system performance and evaluate heat transfer enhancement using nanofluids as heat transfer fluids, numerical work to define the macroscopic behavior of nanofluids and numerical work focused on the microscopic behavior of nanofluids to explain the observations. Besides these research subjects, independent review articles summarizing the latest research and knowledge on the subject are published continuously.

2.2. Production Methods

The methods to produce nanofluids can be evaluated in two general groups: single step methods and two step methods [4]. This section will introduce both types of production, and stress the difference between the methods.

2.2.1. Single Step Methods

Single step methods are production methods in which, the nanofluid is synthesized in a single step work. In other words, the nanofluid is produced completely as the combination of base fluid and nanoparticles simultaneously in one step. The commonly

used methods producing nanofluids in single step are the wet-chemical method, VEROS (Vacuum Evaporation onto a Running Oil Substrate) method and SANSS-Vacuum (Submerged Arc Nanoparticle Synthesis System) method. Nanofluids produced by single step methods are more stable nanofluids and more evenly distributed nanoparticles.

Wet-chemical method is a common single step method which allows the production of most nanofluids by simple modifications. This method, presented by Zhu *et al.* [13], is proposed as an effective method to prepare Cu / EG nanofluids. Modified wet-chemical method is based on the reduction of $\text{CuSO}_4 \cdot 5\text{H}_2\text{O}$ by $\text{NaH}_2\text{PO}_2 \cdot \text{H}_2\text{O}$ in ethylene glycol under microwave irradiation [6, 13, 14]. The results of the process show that the properties of resulting nanofluid and the reaction rate are dependent to the added amount of $\text{NaH}_2\text{PO}_2 \cdot \text{H}_2\text{O}$ and adoption of microwave irradiation. The wet chemical method is used for various nanofluids. Common examples introduced in literature are as CuO / Water [15] and Fe_3O_4 / Water [16].

A modified version of the VEROS method for nanofluid production process, also called as direct evaporation method, is developed in 1997 in Germany [2]. This method is designed for direct evaporation of nanocrystalline particles into the low vapor pressure fluids. The base fluid is put in a rotating cylinder, in the middle of which, the source material is vaporized. Meanwhile, cooling is applied to the fluid to maintain the desired temperature. The evaporated particles condense when contacted with the cooled fluid. This method gives effective results in terms of the resulting nanofluid characteristics. However, it can only be applied to low pressure fluids. Therefore, its applications are limited. Also, the method is not suitable for large amounts of production.

SANSS method is an effective method for the production of nanofluids uniformly distributed nanoparticles in the deionized water. The first application of SANSS method for nanofluid production was for producing CuO particles in deionized water [17-19]. The synthesis is possible through a pure copper rod being submerged in a dielectric liquid in a vacuum chamber. With a proper power source, an arc is produced, which heats the rod to a temperature of 6000 - 12000 °C. The heat vaporizes the metal rod nearby as well as the deionized water. Through nucleation, growth and condensation of the metal and the water, metal nanoparticles in deionized water is reached as a result.

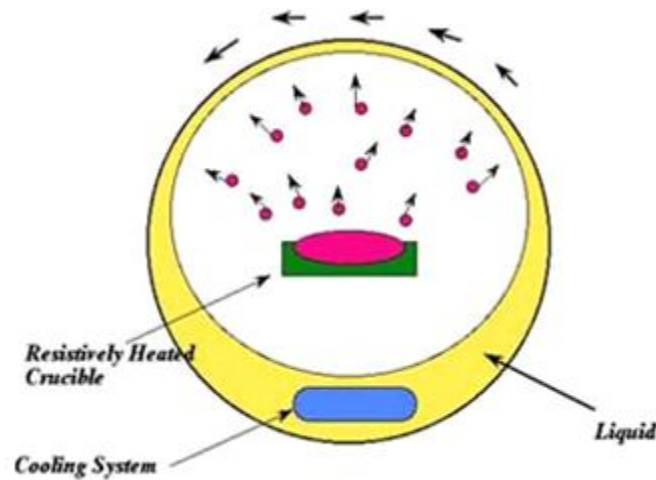


Figure 1.1. SANSS Process [19].

The main purpose for the development of single step methods was to produce nanoparticles. It is observed however, that the separation is difficult after the production of the nanofluid by these methods [5]. The crucial advantage of single step methods is that the processes of drying, storage, transportation and dispersion of nanoparticles are avoided, and therefore the total cost for mass production is dramatically reduced [9]. The disadvantages of these methods are, however, the large variation in nanoparticle size distribution and the difficulties in separation of the particles from the fluid if required. It should also be noted that only low vapor pressure fluids are compatible with this process [9].

2.2.2. Two Step Methods

Two step methods are nanofluid production methods, in which the nanoparticle is produced independently and suspended into the base fluid afterwards. The production processes of the particles, as well as the methods for mixing of nanoparticles to the fluid differ and affect the properties of the nanofluid in terms of stability, uniformity and thermal performance [20]. Experimental results show that in two step methods the selection of the method is far more important with respect to the single step methods [20].

Especially when the stability of the nanofluid is considered, the influence of the mixing method is extremely significant, and can be considered as one of the dominant factors to determine the stability. Literature indicates that nanofluids produced with two step methods may have disadvantage in long term stability with respect to nanofluids produced with single step methods [9]. However, the advantages of two step methods are the simplicity and of production and the ability of producing large amounts of nanofluids in short amount of time.

Several methods have been developed throughout the last 15 years in order to produce nanoparticles. Common methods used for this application can be listed as inert gas condensation, chemical vapor deposition and mechanical alloying. Nanofluid production methods can be divided in two main subgroups: physical / mechanical methods and chemical methods.

Mechanical methods generally include ultrasonification using a probe or a bath [21]. The particles, provided separately by special techniques or acquired commercially are dispersed into the base fluid in a bath. The suspension is mixed by a probe or shaking bath in ultrasonic speed for required time.

Chemical methods include the application of surfactants and carbon nanotube (CNT) functionalization by using acids [21]. Using chemical surfactants changes the wetting or adhesion behavior of the fluid, reducing the tendency for agglomeration. However, the surfactants have the disadvantage of causing the contamination of the heat transfer media and producing foams when heating. Moreover, when applied to carbon nanotube solutions the surfactant may increase the thermal resistance between the nanotubes and the base fluid due to the attachment behavior of surfactant molecules to the CNT particle surfaces. As a result, this increase in thermal resistance reduces the thermal conductivity enhancement of the fluid [22]. Chemical functionalization on CNT nanofluids involves using acids with high temperature to treat the CNTs, increasing their hydrophilic behavior [21]. Studies show that the CNT nanofluids show the best dispersion by the method of chemical functionalization [21]. However, this treatment may cause damage on CNT particles [23].

2.3. Stability of Nanofluids

2.3.1. Importance of Stability

Stability of nanofluids is a desired and important property in their consideration for the use as heat transfer fluids. It is a crucial requirement for a fluid to be stable for long term proper use. Therefore, nanofluid stability has to be determined and confirmed before practical applications. Investigation of stability in literature indicates promising results, separating the nanofluids decisively from classical colloidal suspensions.

The reason behind the failure of classical colloidal suspensions as heat transfer fluids until the discovery of nanofluids is their stability related problems [1, 2]. Studies indicate that the instability of the colloidal suspensions causes several problems such as clogging the channels due to the sedimentation, losing the uniformity of fluid properties, decreasing the thermal conductivity of the fluid and causing erosion in the walls [24]. These problems prohibited the consideration of classical colloidal suspensions to be used as heat transfer fluids so far. The results of studies on nanofluids, however, showed very high stability with respect to other suspensions, making them considerably a more favorable candidate for practical use.

2.3.2. Definition of Stability

A proper definition of stability can be specified as the ability of a suspension to conserve its uniformity for physical properties throughout the entire volume independent from time. In other words, for a stable suspension, the properties such as the density, particle concentration, thermal conductivity, average particle and cluster size have to be similar in each part of the suspension and these properties have to be constant with respect to time. The change in these properties indicates the loss of stability and is considered as a threat for long term use. Through the evaluation of colloidal suspensions two general behaviors have been observed to disrupt the overall stability: agglomeration and sedimentation.

Agglomeration is defined as the clustering of the nanoparticles in the fluid by joining together and forming larger particles due to the attractive forces or collisions in between. Due to the increase in number of particles in clusters, the average particle size in the suspension also increases. The studies show that agglomeration and clustering directly affect physical properties such as thermal conductivity [25]. Furthermore it is observed that agglomeration triggers further and faster loss of stability. It has been observed that agglomeration causes clogging in microchannels and disrupts uniformity [25]. Due to the uniformity disruption, the fluid tends to show different physical and thermal characteristics in different sections.

Sedimentation is precipitation of the particles due to the gravitational force. The problems caused by sedimentation are accumulation and particle concentration decrease. The precipitated particles accumulated at the base cause clogging and erosion. Since the precipitated particles do not behave as a part of the nanofluid, the volumetric concentration of the particles in the nanofluid also decreases due to the sedimentation, and therefore the thermal conductivity enhancement of the nanofluid decreases. Moreover, fluid uniformity is disrupted due to sedimentation. The downwards movement of the particles causes decrease in particle volumetric concentration at upper layers and an increase in particle volumetric concentration at lower layers. This loss of uniformity leads to different physical and thermal characteristics in different layers of the fluid.

Agglomeration and sedimentation tend to trigger each other in a colloidal suspension. Due to agglomeration, particle clusters with higher size and increased mass are formed throughout the fluid. Due to the increased mass, the effect of the gravitational force increases, which causes faster sedimentation. On the other hand, due to sedimentation, uniformity of the nanofluid is disrupted, and increase in particle concentration in the lower segments of the fluid observed. The increased concentration in these segments causes reduction in the average distance between particles, and therefore higher probability of collision as well as higher attractive forces occur, which causes increased agglomeration. Therefore, it can be concluded that each step taken to prevent agglomeration or sedimentation has an effect on both sides.

Nanofluids have shown improved characteristics in terms of stability with respect to the other colloidal suspensions [20]. This increase has been explained by the effect of particle size on gravitational force and Brownian forces [25]; small random forces on each particle, caused by the collision of particles with fluid molecules. In classical colloidal suspensions, due to larger effective particle size, the order of the gravitational force is significantly greater than the other forces on the particle. Therefore, gravitational force is the dominant force on the particle on determining the general behavior of the particle, directing the particle downwards. In nanofluids, the particle size is small enough to reduce the order of gravitational force into the order of other forces. Therefore, the random effect of Brownian forces gain importance. Furthermore smaller size decreases the chance of collision of the particles, and improves fluidity.

Despite the high interest on the topic, there is no universally accepted method to measure stability. In literature, several methods have been proposed and are being used to investigate the stability of nanofluids experimentally and numerically. These methods generally concentrate on one of two aspects, agglomeration or sedimentation. However, in some more recent methods, both factors are in focus.

Sedimentation method is one of the most reliable and simple methods for the measurement of the stability. In this method, the variation of particle volumetric concentration is measured by special apparatus and photography. The suspension is considered stable as long as the volumetric concentration of the particles does not change. The disadvantage of this method is the long time requirement for results. One application of the sedimentation method can be seen in Hwang's studies [26, 27], where the volumetric concentration of the particles has been obtained by UV-vis spectrophotometer, and the variation on the concentration has been observed.

One method, used by Yang and Du [28] estimates the dispersion stability by measuring the absorbency. Absorbency is defined as the product of molar absorptivity, optical path and molar concentration. A direct relation between the absorbency and the dispersion stability is assumed throughout the study. The results of the study for different nanofluids are given in terms of absorbency and the values are used in stability comparison.

Another common method, taking agglomeration into focus is using direct light scattering to measure the average particle diameter. The increase in average particle diameter indicates agglomeration. The size distribution is assumed to be directly related to stability in this method. This method is widely used throughout the literature. An example can be seen in the study of Shima *et al.* [29].

Ganguly *et al.* [30] embarked from the theory for colloidal stability, which describes the total interaction energy between the particle pairs as a function of two factors: the separation distance between them and the balance of the repulsive and attractive forces. The stability is confirmed by the dominant electrostatic repulsive character of the particles. It is, however, observed and accepted that some agglomeration is inevitable.

Bhattacharya [31] used in his numerical study a layered fluid model to investigate the fluid stability, taking the sedimentation as the primary subject for stability. He divided his control volume to horizontal layers with equal thickness, and calculated the volume fraction in each layer. The model started with particles aligned in face centered cubic alignment, and the change in volumetric concentration after a considerable number of time steps has been calculated by using the new coordinates for each particle. The volumetric concentration of the control volume has been visualized with a graph layer by layer, giving the average distribution. The estimation for the stability is made by evaluating the volumetric concentration difference of layers with respect to each other and overall control volume particle volumetric concentration. It is observed that as a general behavior the particles tended to accumulate in lower segments of the control volume.

Another numerical method to measure the stability is proposed by Weiting *et al.* [32] in which the average particle downwards displacement is chosen as the focused property. In this model, the control volume is taken as an open space control volume, whenever a cluster leaves the control volume from any direction, another particle with the same size, same properties and same kinematics enter from the opposite direction, so that the volumetric concentration is always ensured. The particle movements in the control volume are simulated by calculating every force on the particle. During the simulation, both agglomeration and sedimentation are considered. The model also takes the clustering effect into account, increasing the size of the cluster whenever another particle or cluster is added to it. It obtains the average particle displacement in the downwards direction in order to

analyze stability, and the stability is assumed to be totally disrupted when the average downwards particle displacement reaches the total value of the value of control volume height.

As it can be seen from the examples, various methods are used to estimate the stability of a nanofluid. Despite the common use of these methods and several other ones proposed in other studies, none of them has been accepted universally to examine the stability of a nanofluid since now. Therefore, one must be careful when comparing the stability results of different studies, since they may have used different criteria to define the colloidal stability.

2.3.3. Affecting Factors and Stability Improvement Methods

Stability of nanofluids and determination of the relevant factors to enhance the stability are popular areas of interest deeply investigated through the literature. After the observation of extraordinary nanofluid stability with respect to classical colloidal suspensions, the second step was to investigate the reasons behind this behavior.

One major research objective on colloidal suspensions and nanofluids can be defined as to increase their stability for long term use and practical applications. Despite the considerably higher stability of nanofluids with respect to classical colloidal suspensions, most nanofluids are still in need of further improvement in stability for practical use. Several methods and treatments are commonly used in studies to provide higher stability and less accumulation.

2.3.3.1. Average Nanoparticle Size and Variation. Average nanoparticle size can be considered one of the dominant variables influencing the stability of the nanofluid. Being the major difference of nanofluids from the classical colloidal suspensions, the particle size is the most significant factor causing the extraordinary high stability of nanofluids. The reason for this influence is the change in force balance on particles. Each particle in a suspension is under the influence of five different forces [31]. Three body forces acting on the particles are the attractive Van Der Waals force, the repulsive electrostatic force due to the electric double layer and the gravitational force. Besides these body forces, the particles are also subjected to resistive force by the fluid molecules. The final force acting

on the particles is the random Brownian force due to the collision with the fluid molecules. Among these forces, the contribution of the gravitational force is strongly dependent on the particle size. In large particles (>100 nm) the gravitational force has a considerably higher magnitude in comparison to other forces, and therefore it acts as the dominant force on the particle, militating the overall particle movement downwards and disrupting stability. If the particle size is smaller than 100 nanometers, in other words the particle is a nanoparticle, the order of magnitude for the gravitational force reduces into the order of other forces and the particle motion is not dominated by the gravity. The stability increases as the tendency for downwards motion decreases. In this case, the random effect of Brownian forces gains importance [25].

2.3.3.2. Choice of the Production Method and Surfactants. As specified before, two general methods are possible to produce nanofluids; single step methods and two step methods. Studies show that the choice of the production method is one of the important factors affecting the stability. In general, it is observed that single step production methods give better results in terms of stability [25]. The single step preparation of the nanofluids provides a better distribution and a more steady condition against accumulation with respect to separate preparation and mixing. Throughout the literature, various methods for production have been proposed and used to reach stable and even distributions.

Ultrasonification process and application of dispersants are commonly used to increase the stability, and produce evenly distributed particles in a fluid. Ultrasonification may be applied in two types: mixing the fluid with a small rod vibrating in ultrasonic speed and shaking the fluid container in ultrasonic speed. Ultrasonification process has to be used carefully, since the effect reverses after the optimum time of ultrasonification. It has been observed that ultrasonification after passing the optimized duration causes higher agglomeration and rapid sedimentation of the particles [25].

During the production, application of surfactants is another common solution to prevent agglomeration. The addition of surfactants increases the stability dramatically, providing especially enormous enhancement in nanofluids using water as base fluid [25]. The amount of applied surfactant is an important parameter for stability. Using insufficient surfactant will not increase the stability enough, and using more than sufficient surfactant

may cause thermal resistance between the particles and the fluid, decreasing thermal enhancement [21, 25].

Common surfactants for stability enhancement purpose can be listed as sodium dodecylsulfate (SDS), SDBS, cetyltrimethylammoniumbromide (CTAB), dodecyl trimethylammonium bromide (DTAB), sodium octanoate (SOCT), hexadecyltrimethylammoniumbromide (HCTAB), polyvinylpyrrolidone (PVP) and Gum Arabic [25]. Using the proper surfactant type among anionic, cationic or nonionic surfactants for the suspension in consideration has crucial importance.

In literature several other methods are available to increase nanofluid stability. As an example, Kim *et al.* proposed a new production technique for the increased stability using pulsed laser ablation [33]. He applied laser irradiation on gold nanoparticles which are suspended in water. The results indicated that the suspension stayed stable up to one month.

2.3.3.3. pH Value. Studies indicate that the pH value of the suspension is another factor for the stability of the nanofluid. Controlling the pH value of the suspension is therefore another preferable method to increase the stability. In literature, acid treatments have been used on the nanofluids for that purpose. Xie *et al.* showed that with a simple acid treatment the stability may increase anomalously. Lee *et al.* observed on their work on Al_2O_3 - water nanofluids with different pH values [34], that the pH value has a direct relevance with the agglomeration. When the pH value of the suspension reduced to 1.7, the agglomeration also reduced to 18%, and when the pH value increased to 7.66, the agglomeration also increased to 51%. It is also observed that the average cluster size changes with respect to the change on pH value. The reason for this difference is given as the change in Zeta potential; the electric potential existing between the particle surface and the dispersing liquid at the slipping plane, and therefore the reduction in repulsive forces [25]. The reduced repulsive forces cause change in force balance in favor of attractive Van Der Waals forces, increasing the tendency of the particles to aggregate.

2.4. Thermal Conductivity of Nanofluids

2.4.1. Thermal Conductivity Increase

By definition, thermal conductivity is a significantly important influencing factor for thermal performance of the nanofluids. In a suitable system, thermal conductivity and heat convection of the working fluid are high and the power requirement of the system is low. In general it is observed that the nanoparticle addition increases the thermal conductivity exceptionally.

To determine the influence of the nanoparticles on the fluid, experimental and numerical research for different methods, conditions, nanofluid materials, concentrations, size distributions, production methods and measurement techniques has been done. The main purposes of the studies are to determine the amount and limits of the heat transfer enhancement, to find the factors affecting the thermal performance and their amount of influence, and to gather the knowledge about the microdynamics to explain the spectacular increase with respect to other colloidal suspensions.

2.4.2. Research on Factors Affecting Thermal Conductivity

As an important point of interest in the topic, the investigation of the factors affecting thermal performance has been the focus of most studies on the subject of nanofluids. Besides the results of the experimental studies, several review articles have been published containing the summary of the results, pointing the consistency, similarities and conflicts between the separate studies.

2.4.2.1. Particle Material. Theoretically any solid nanoparticle can be used as additives for nanofluids. However, due to the desire for high thermal conductivity, the availability of production methods for materials and the material costs have limited the materials of nanoparticles to a fewer number. In literature four different types of nanoparticles are used since now: (i) metallic particles (Cu, Al, Fe, Au, Ag, etc.); (ii) nonmetal particles (Al_2O_3 , CuO, Fe_3O_4 , TiO_2 , SiC); (iii) carbon nanotubes; (iv) nanodroplets. Metallic and nonmetal particles as well as carbon nanotubes are widely investigated throughout the literature.

However, nanofluids dispersed with nanodroplets are a more recent area of study [35]. Preliminary studies on the topic indicate that this type of nanoemulsion fluid has the advantage of long-term stability and easy mass production.

Despite the fact that the particles with materials of high thermal conductivity generally show better enhancement on heat transfer, the studies show that the material of the particle is not a dominant factor on the enhancement. Adjustment of other factors such as particle concentration and size may lead to more efficient enhancements with particles of lower thermal conductivity. To illustrate, Eastman *et al.* [11] measured thermal conductivity enhancement of nanofluids with CuO and Al₂O₃ as particle material, and concluded that CuO nanoparticles caused a greater enhancement on the fluid although CuO has a lower thermal conductivity. Other studies have been fulfilled for TiO₂ and Al₂O₃ nanoparticles by Murshed *et al.* [36] and Xie *et al.* [37]. The volumetric concentrations (5%) and base fluids (water) for both studies is same, and the average particle diameters were 15 nm for TiO₂ and 20 nm for Al₂O₃. When the results were compared it is seen that the thermal conductivity increase in of TiO₂ nanofluids are more than 10% greater with respect to the increase in Al₂O₃ nanofluids despite the opposite ratios for particle thermal conductivities.

The studies of Patel *et al.* [38] on gold (particle diameters 10-20 nm) and silver (particle diameters 60-80 nm) nanoparticles with water showed similar thermal conductivity enhancements for both types of particles (5% in room temperature), however, it should be noted that the average size of gold and silver particles were not same, and particle size is an important factor on the enhancement. Among the same study, Patel *et al.* also investigated the nanofluids containing the same nanoparticles, using toluene as the base fluid however. This experiment has been done on a temperature of 60 °C, and resulted in 16.5% increase in Ag-toluene nanofluids and 21% in Au-toluene nanofluids.

2.4.2.2. Particle Size. As the strongest difference of nanofluids from classical colloidal suspensions, average particle size of a nanofluid is an important variable affecting the thermal conductivity increase directly. The enormous increase in thermal properties of nanofluids with respect to classical colloidal suspensions has been directly related to the average diameter of the particle as a general point of view, and different explanations have

been proposed for the spectacular increase. These explanations and models will be explained in Section 2.4.3.

The increase of enhancement due to smaller particle size was predicted initially by Jang and Choi [39], and studies on the topic confirmed that the particle size is one of the dominant factors in terms of heat transfer enhancement [40-44]. Various experimental studies have been focused on the effect of the particle size to the thermal conductivity of a nanofluid, and the results were supported by theoretical and numerical models in order to understand the reasons behind the influence.

Using Al_2O_3 / water nanofluid with particles of different size, Teng *et al.* observed the effect of the particle size on thermal conductivity of the fluid [45]. Nanoparticles in size of 20 nm, 50 nm and 100 nm were dispersed into water and measured the thermal conductivity change. The experiments were repeated in 10°C, 30°C and 50°C for the evaluation of the consistency. It was observed that smaller particles cause higher enhancement on thermal conductivity. Furthermore, the thermal conductivity enhancement difference between 20 nm nanoparticles and 50 nm nanoparticles is considerably greater than the difference between 50 nm particles and 100 nm particles. This result shows that the thermal conductivity increase rate grows anomalously as the particle size decreases.

While investigating the effect of clustering on nanoparticles, Karthikeyan *et al.* [40] also witnessed the influence of the particle size on thermal properties. They worked with CuO – water nanofluid, consisting of CuO nanoparticles of 8 nm, a very small diameter with respect to the particles used in literature. As a result, the highest thermal concentration increase with CuO nanoparticles has been noted as 54% increase for 1% volumetric concentration for EG and 31.6% increase for the same volumetric concentration in water.

Feng *et al.* [46] proposed a numerical model to calculate the effective thermal conductivity of nanofluids. The model is expressed as a function of the nanolayer thickness, particle size, particle volume fraction and the thermal conductivities of suspended nanoparticles and the fluid. When compared with experimental results, the predictions of the model were accurate in most cases, despite a few deviations were observed in comparison with the their reference studies. The model indicated a remarkable

influence of particle size, showing a significant increase especially for particles smaller than 15 nm. According to the model the particle size effects are minimal between 65 to 40 nm, showing a slight increase for particle size decline between 40 to 20 nm. From 20 to 10 nanometer sized particles the increase in thermal conductivity is considerably high and the particles smaller than 10 nanometers enhance the fluid dramatically. To illustrate the sudden increase in small diameters, the comparison of the modeling results for two sample nanofluids can be evaluated. For a CuO - water nanofluid with 21 nm particles, 3% volume fraction and 2 nm nanolayer thickness the model predicts a thermal conductivity enhancement of 11%. When the same conditions applied to the same nanofluid, and only the average particle size is reduced to 3 nm, the enhancement rises to 21% almost doubling itself.

2.4.2.3. Particle Shape. The effect of the particle shape on the thermal performance was already known for classical colloidal suspensions, leading to the proposal of Hamilton & Crosser [47] correlation to estimate the thermal conductivity of suspensions. In this correlation the particle shape is taken into the account by a variable of “shape factor”, significantly affecting the result of the estimation. Therefore, it was foreseen that the particle shape also influenced the thermal performance of nanofluids. Most nanoparticles are spherical or cylindrical shaped, whereas carbon nanotubes (CNT's) form long tubes with very high aspect ratios. Research on the topic indicates that the physical shape of the nanoparticles is also considered as a variable for the calculation of the thermal conductivity of a nanofluid.

2.4.2.4. Base Fluid. Base fluid and its thermal and physical properties are effective on the thermal conductivity of the whole suspension. The purpose addition of the particles is to increase that base thermal conductivity. Therefore, thermal conductivity of the base fluid gives is the lower limit of the thermal conductivity of the nanofluid so that for a high thermal performance nanofluid, fluids with higher thermal conductivity are selected as the base fluid.

Classical thermal conductivity calculation methods (Maxwell correlation, Bruggeman correlation, Hamilton & Crosser model) for colloidal suspensions show relevance between the base fluid conductivity and the suspension conductivity [5, 48].

However, the amount of enhancement due to particles decreases by the increase in base fluid thermal conductivity and as the thermal conductivity difference of the fluid and the particle is smaller.

Common base fluids in the literature are water, oil, acetone, decene and ethylene glycol. Xie *et al.* [37] studied nanofluids with the same nanoparticles in terms of size and material and same operating conditions to investigate the effect of the base fluid, taking only the base fluid as a variable into account. As base fluid water, ethylene glycol, and pump oil were used to determine the effect of the base fluid. Al_2O_3 nanoparticles of an average size of 60.4 nm have been dispersed into the fluids and the thermal conductivity values have been measured. The results indicate that the nanofluid with pump oil has the greatest enhancement with a ratio of 38%, followed by the nanofluid with EG (29%) and water (20%). On the overall thermal conductivity values, the opposite direction on the order is valid.

Xie *et al.* also studied the effect of the base fluid on the nanofluids with carbon nanotubes [49]. During the studies 15 x 30 μm nanotubes have been dispersed by a volume fraction of 1% on different base fluids. The results showed that the maximum thermal conductivity enhancement among three tested base fluids has been obtained by EG by 19.6%. The tubes caused 12.7% enhancement on decene, and 7% enhancement on water. A similar study has been done with Choi *et al.* [50] by using 25 x 50 nanotubes with the same concentration, using poly oil as the base fluid. A spectacular increase of 160% has been observed as a result.

The results are consistent with each other as well as the correlations and general models, since water has the highest the thermal conductivity among the tested fluids, followed by EG and pump oil at last. It can be concluded from these results, that the thermal conductivity increases with the higher thermal conductivity of the base fluid. When the enhancement ratios are evaluated, however, the ratio increases with fluids with lower thermal conductivity. This is an expected behavior, since the distance between the thermal conductivities of the base fluid and the particle is greater for low thermal conductivity fluids, and therefore the effect of the particles increase.

The studies of Lee *et al.* [51] included a set of experiments with nanofluids using Al_2O_3 and CuO nanoparticles with water and EG base fluids. The particle diameters were 18.6 nm for CuO and 24.4 nm for Al_2O_3 . The nanofluids have been tested on different volumetric concentrations, and the results indicate that in each concentration and particle type, the rates of enhancement for EG nanofluids are higher. To illustrate the difference the results at 2% of volumetric concentration can be observed. The thermal conductivity enhancement by using CuO is calculated about 9% for EG and 7% for water. For Al_2O_3 particles, the enhancement is observed as 6% for EG and 5.5% for water.

Xie *et al.* [37] reached on nanofluids containing alumina nanoparticles the same conclusion on nanofluids with alumina nanoparticles. For various base fluids the enhancement increases as the base fluid thermal conductivity decreases. The same results have been observed on graphene nanofluids [52] and on diamond nanofluids [53] by Yu *et al.* The consisting conclusions imply the pattern of the general behavior.

However, contradicting results have also been obtained throughout the literature. Xuan *et al.* [54] used Cu nanoparticles with 100 nm average diameter on water and oil. At a volumetric concentration of 7.5%, the nanoparticles increased the thermal conductivity of water by 78%, whereas the enhancement on oil is by 43%. They did not give any particular reasons for this contradiction.

2.4.2.5. Effect of Stability. Thermal performance of the fluid is affected directly and indirectly by both factors of stability; agglomeration and sedimentation. Since the stability is a function of time, the thermal performance of the fluid is also changes with respect to time. The effects of stability may be summarized in three topics: loss of thermal property uniformity due to sedimentation, decrease of heat transfer enhancement due to sedimentation and effect of clustering.

Particle movement to gravitational direction due to sedimentation causes loss of uniformity in the nanofluid. The different particle concentration rate causes different thermal properties on the top and bottom side of the container.

Sedimentation has an indirect negative effect on thermal enhancement of nanofluids due to decrease of volumetric concentration. Sedimented particles accumulate on the bottom side separating themselves from the fluid. These particles do not move in the fluid, and do not have any effect on the nanofluid anymore. In conclusion, the nanofluid loses particles, and the overall particle fraction decreases. The thermal properties are affected with respect to new lower concentration.

Clustering is the nanoparticle behavior of forming larger particles. It is caused by agglomeration, and the studies show that clustering affects the thermal conductivity of the fluid significantly. The effect of clustering has been the focus of several studies. Karthikeyan *et al.* [40] studied the effect of clustering on thermal conductivity on nanofluids containing CuO as the particle and water or ethylene glycol as base fluid. With an average particle diameter of 8 nm and volume fraction of 1% they encountered a very high thermal enhancement of 54%, the thermal conductivity of the nanofluid decreased with the elapsed time. The clustering of the particles was also confirmed microscopically. They concluded that the particle size, fraction and clustering have significant influence on thermal conductivity of suspensions.

Hong *et al.* [55] studied the effect of stability and clustering on thermal properties using nanofluids of Fe nanocrystalline powder and ethylene glycol. The nanofluid was prepared as a result of two step method, providing Fe nanoparticles first by synthesis through chemical vapor condensation process and mixing them afterwards into ethylene glycol by using ultrasonic cell disrupter. The mean particle diameter is given as 10 nm. Sample nanofluids of same material compositions and different concentrations from 0.2% to 0.55% were exposed to ultrasonification process of different time intervals from 0 to 70 minutes to observe the effect of clustering and stability, and the thermal conductivity of each nanofluid in each time interval is measured. For each concentration it is observed that the ultrasonification time increases the thermal conductivity up to a certain point of time (an average value of 50 minutes in the study in consideration), whereas the rate of increase slightly decreases in time. After reaching the maximum at the ultrasonification time of 50 minutes, the thermal conductivity decreases, and each nanofluid has lower thermal conductivity at 70 minutes ultrasonification with respect to 50 minutes. As the volumetric concentration of nanoparticles increase, the required time to reach the maximum thermal

conductivity also increases. As another part of the study, the thermal conductivity change with respect to time after the ultrasonification process is measured, and the change in average particle cluster diameter is observed. The results indicate that the thermal conductivity of the fluid decreases with time and converges to a certain enhancement rate, whereas the average particle diameter increases rapidly also converging to a limiting value. Considering these both observations, Hong *et al.* concluded that there is a direct relevance with the rate of clustering and decrease of thermal conductivity.

Prasher *et al.* [56] studied the thermal conductivity enhancement due to aggregation numerically, testing a cluster-cluster aggregation algorithm on a numerical cubic lattice nanofluid model on different concentration values of 0.5%, 1%, 2% and 4%. The results of the study indicated that the thermal conductivity of nanofluids based purely on conduction phenomenon and it can be significantly enhanced by the aggregation of particles. Another conclusion of the study was that the enhancement due to aggregation and clustering is a strong function of the chemical dimension of the aggregates and the radius of gyration of the aggregates.

Yang *et al.* worked on the effect of dispersion stability on thermal conductivity of binary nanofluids [57]. Using TiN-ammonia and water nanofluids. By increasing TiN and ammonia content, the change in thermal conductivity of the nanofluid is evaluated and the optimum parameters estimated. The mass fraction of the ammonia was changed from 0% to 25% in 5% increments, and the TiN particles with an average size of 15 nm have been used at a mass concentration range from 0.25% to 2% in 0.25% increments. It is observed that the fraction of nanoparticles and ammonia are the key parameters that affect dispersion. The results showed that the dispersion of the nanofluid first increases with the addition of ammonia, reaching a maximum point, and decreasing after that point with further addition. The same result also applies to nanoparticle addition. The dispersion first increases with particle fraction increase, and then decreases with further addition. The dispersion stability directly affects the thermal conductivity, better dispersion inducing higher conductivity. The optimum point for dispersion and the thermal conductivity is found as 5% mass fraction of alumina and 1.5% mass fraction of nanoparticles.

2.4.2.6. Volumetric Concentration of Nanoparticles. Particle concentration is one of the primary factors affecting the thermal properties in every type of colloidal suspensions, including nanofluids. As an important and easily adjustable factor, it is widely investigated throughout the research on nanofluids in literature. Experiments show that effect of the volumetric concentration does not only affect the thermal conductivity, but also the stability and rheological properties of the fluid.

Correlations taking different characteristics into account have been proposed to calculate the thermal conductivity of colloidal suspensions by Maxwell, Bruggeman, Hamilton & Crosser, Xue and Yu & Choi [58, 59]. Maxwell and Bruggeman correlations have been driven to calculate the colloidal suspensions of normal size, and give relatively low and inaccurate results for nanofluids, underestimating the thermal conductivity enhancement. Maxwell correlation [60], as one of the oldest thermal conductivity estimation methods for colloidal suspensions developed in 1873, simply estimates the thermal conductivity of the nanofluid by the thermal conductivities and volume fractions of the components. Maxwell correlation is most commonly used method to predict the thermal conductivity of the nanofluid in literature.

$$k_m = \frac{k_p + 2k_b + 2(k_p - k_b)\phi}{k_p + 2k_b - (k_p - k_b)\phi} k_b \quad (2.1)$$

Where k_m represents the thermal conductivity of the nanofluid, k_b is the thermal conductivity of the base fluid, and k_p is used for the thermal conductivity of the nanoparticle. ϕ is used for particle volumetric concentration. Bruggeman correlation [61] also takes the interactions among randomly distributed particles into account.

$$\phi \frac{k_p - k_m}{k_p + 2k_m} + (1 - \phi) \frac{k_b - k_m}{k_b + 2k_m} = 0 \quad (2.2)$$

Both Maxwell and Bruggeman theories are general effective medium theories. They are used to describe distinct cases. Hamilton & Crosser model [47] is developed for more accurate estimations for liquid-solid mixtures containing non-spherical particles. The effect of the particle shape is represented in the correlation by introducing a shape factor n .

$$k_m = \frac{k_p + (n-1)k_b - (n-1)(k_b - k_p) \phi}{k_p + (n-1)k_b + (k_b - k_p) \phi} k_b \quad (2.3)$$

Xue model [62] is an extension of Maxwell correlation for nanofluids, including the large axial ratio and the space distribution of carbon nanotubes. The method is primarily defined to calculate the thermal conductivity of nanofluids containing nanotubes, since the special axial shape of the nanotubes does cause inaccuracy in classical models.

$$k_m = \frac{1 - \phi + 2\phi \frac{k_p}{k_p - k_b} \ln \frac{k_p + k_b}{2k_b}}{1 - \phi + 2\phi \frac{k_b}{k_p - k_b} \ln \frac{k_p + k_b}{2k_b}} k_b \quad (2.4)$$

Yu and Choi [63] developed an accurate correlation for nanofluids including the effect of nanolayer with an equivalent thermal conductivity. The method gives accurate results for common nanofluids.

$$k_m = \frac{k_{pe} + 2k_b + 2(k_{pe} - k_b)(1 + \sigma)^3 \phi}{k_{pe} + 2k_b - (k_{pe} - k_b)(1 + \sigma)^3 \phi} k_b \quad (2.5)$$

On the equation above, σ is the ratio of the nanolayer thickness to the original particle radius and k_{pe} is the equivalent thermal conductivity and its definition is given below by using γ , the ratio of nanolayer thermal conductivity to the particle thermal conductivity:

$$k_{pe} = \frac{|2(1 - \gamma) + (1 + \sigma)^3(1 + 2\gamma)|\gamma}{(\gamma - 1) + (1 + \sigma)^3(1 + 2\gamma)} k_p \quad (2.6)$$

Current studies show that the classical correlation methods underestimate the thermal conductivity enhancement of the nanofluid. These methods underestimate the enhancement whereas the increase surpasses the estimations by a large amount due to micro-transactions. Therefore, the formulations of Xue [62] and Yu & Choi [63] were introduced. The causes for this increase are introduced in Section 2.4.3.

Nanoparticle concentration also has a negative effect on the thermal performance due to the increased pressure drop and pumping power requirement [64]. However, studies show that, the overall behavior of the thermal performance is dominated by the positive effects of the nanoparticles. A comprehensive set of studies has been done throughout the literature in order to evaluate the effect of nanoparticle concentration.

A study carried out by Lee *et al.* [51] in 1999, in which different nanofluids at different concentrations are evaluated to clarify the dependence of the thermal conductivity enhancement with respect to particle fraction increase. The nanofluids chosen for the study were using water and ethylene glycol as base fluid and copper oxide II (CuO) and alumina as the particle. The thermal conductivity ratios of the nanofluids to the base fluid were observed at different particle fractions from 1% to 5%. The results implied an almost linear dependence of thermal conductivity to the particle concentration.

Eastman *et al.* studied the thermal conductivity increase in copper and ethylene glycol nanofluids in 2001. Through the experiments, old and fresh copper nanoparticles as well as copper and acid together were used in the nanofluid and a range volumetric concentration up to 1% were used. The results confirmed with the previous experiment, showing linearity in thermal conductivity and particle volume concentration also in copper and ethylene glycol nanofluids. However, by the addition of acid, disturbance in the linearity is observed whereas the thermal conductivity increased rapidly in very small amounts of concentrations.

Patel *et al.* [38] studied water and toluene based nanofluids with gold and silver nanoparticles to evaluate the effect of volumetric concentration. They studied in a range of 30-60°C Temperature and observed 7-14% thermal conductivity increase. The results indicated that the motion of particles is an important factor affecting the thermal conductivity, and the increase is almost a linear with the increase of particle volume fraction.

Nonlinear increase of thermal conductivity due to nanoparticle concentration increase was first observed on a fluid with carbon nanotubes dispersed in an oil matrix

material prepared by Choi *et al.* [50]. The study, having a 150% increase in the oil conductivity with approximately 1% particle volumetric concentration, achieved to be the highest enhancement measured. The increase was nonlinear with the volume fraction despite the linear relationship predictions and had an order of magnitude greater than predicted by existing models. The results were confirmed by Shaikh *et al.* [65]. Later several studies of independent researchers such as Murshed *et al.* [36], Hong *et al.* [66] and Chopkar *et al.* [41] showed that nanofluids with spherical nanoparticles also have nonlinear behavior.

Wen and Ding studied the effect of particle migration on heat transfer characteristics of nanofluids in millimeter sized channels in 2005 [67]. They used channels with diameter of 1 mm, and nanofluids with non-uniform concentration. Their results showed that there is no significant uniformity in particle concentration of nanofluid and the thermal conductivity due to migration.

Duangthongsuk *et al.* [6] studied TiO₂ nanoparticles dispersed in water with volumetric concentrations of 0.2%, 0.6%, 1.0%, 1.5%, 2.0% and compared the results of each nanofluid. The results showed similarities with the previous results, implying that the increase in particle concentration also increases the thermal conductivity of the nanofluid. By comparison of experimental results with the classical correlations of Bruggeman, Wasp and Hamilton & Crosser, the observations indicate increase in thermal conductivity is significantly greater than the calculations. Another conclusion of the study can be expressed as the Yu and Choi correlation gives a more accurate prediction for nanofluids with respect to other methods.

2.4.2.7. Temperature. Temperature can be defined as another variable involving in thermal conductivity enhancement. The studies in the literature show certain conductivity changes due to the temperature of the fluid [6, 38, 48], emphasizing the importance of temperature effects. During the use of nanofluids as heat transfer fluids, the influence of the temperature is an important variable, since the working conditions as well as the environmental temperature restrictions may vary in a large margin in practical applications. Effect of temperature has to be taken into account when estimating thermal performance and characteristics of nanofluids in practical applications.

The influence of temperature change has been the subject of several researches in literature. One of the first studies on the topic has been fulfilled by Das *et al.* [68], using nanofluids with Al_2O_3 and CuO nanoparticles and water as base fluid. Both nanofluids have been tested for 1% and 4% particle volumetric concentration and at temperatures between 21°C and 51°C. The results indicated a direct and strong relevance between the increase in temperature and the increase in thermal conductivity in both nanofluids and each volumetric concentration. To illustrate, the Al_2O_3 - water nanofluid with 4% particle volumetric concentration, the thermal conductivity ratio of the nanofluid to base fluid increased from 1.085% at 21°C to 1.245% at 51°C. Similarly, for CuO-water nanofluid at 4% volumetric concentration, the thermal conductivity ratio of the nanofluid to base fluid increased from 1.14% at 21°C to 1.35% at 51°C. The authors of the article concluded that the temperature has a dramatic effect on the thermal conductivity of a nanofluid and underlined the significance of this dependence for the use of nanofluids as coolants since the coolants generally work under circumstances with higher temperature with respect to room temperature.

Another study has been carried on by Godson and Lal [69] focusing on silver suspended in deionized water nanofluids. The effect of the temperature on the thermal performance is investigated in a range of 50°C to 90°C on suspensions with 0.4%, 0.8% and 1.2% particle volumetric concentration. It is shown that the thermal conductivity of pure water as well as the nanofluid increases with increasing temperature. Pure water thermal conductivity has increased from 0.642 W/mK at 50°C to 0.678 W/mK at 90°C. The temperature has, however, a far greater influence on nanofluids, increasing the thermal conductivity in larger margins in each case. Taking the nanofluid with 0.8% volumetric concentration into consideration as an example, the thermal conductivity is measured about 0.8 W/mK at 50°C whereas it is about 1.495 W/mK at 90°C. Similar increases have been measured for other volumetric concentrations, confirming the positive effect of the temperature.

A similar experiment has been conducted by Yeganeh *et al.* [70] for nanofluids containing diamond nanoparticles and deionized water. Choosing sample particle volumetric concentrations of 1.5%, 2% and 3%, the thermal conductivity enhancement has been measured at a range of 30°C to 50°C. It is observed that in each case, the thermal

conductivity of the fluid is higher at higher temperature. An example result can be shown as the increase in thermal conductivity ratio of nanofluid to base fluid from 1.065 at 30°C to 1.08 at 50°C for a nanofluid of 2% diamond nanoparticle concentration.

These experimental results have guided the theoretical and numerical studies on the topic. Under the enlightenment of these observations, the validity of several numerical works focusing on the thermal conductivity enhancement are also confirmed. As an example to these numerical models the model proposed by Sitprasert and Dechaumphai [48] can be given. This model aims to calculate the thermal conductivity increase by taking several factors into account, including the influence of the temperature. When an Al_2O_3 - water nanofluid with 1% particle volumetric concentration and average particle diameter of 11 nm is simulated by the model, accepting the only variable as the temperature, it gives a direct relevance between the thermal conductivity ratio increase and the temperature. In the interval of 293K and 343K, the thermal conductivity ratio increases from 1.055 to 1.19.

Comparing the results of the studies, it can be concluded that, as a general and consistent behavior, the temperature increase enhances the thermal performance significantly. The thermal conductivity of nanofluids tends to increase with the increasing temperature, and when compared to the thermal conductivity increase of the base fluid of same temperature change, a far higher enhancement is observed in nanofluids.

2.4.2.8. Pretreatment. While preparing nanofluids, solid particles may be subjected to various pretreatment procedures. The main purpose of the pretreatment is to modify the nanoparticle shapes in order to enhance their dispersibility and thereby enhance the stability of the nanofluids. Especially for carbon nanotubes, having been subjected to these chemical and mechanical treatments causes significant changes in morphology and aspect ratio.

Theoretical research on the subject predicts a direct relevance between the aspect ratio and the thermal conductivity, implying thermal enhancement increase with the aspect ratio of particles [71-73]. Therefore, the expectation would be that the thermal enhancement would decrease with increased pretreatment time. However, practical applications of these pretreatment methods showed a different result. When Xie *et al.* [57]

worked on CNT nanofluids to evaluate the effects of ball milling, they encountered an opposite behavior. When the results for CNT nanofluids with different time of ball milling were evaluated, a peak and valley distribution is observed on the thermal conductivity versus ball milling time graph. Thermal conductivity enhancement showed a rapid increase first, made a peak at a certain time, and then decreased until a minimum. The behavior was similar at 0.2%, 0.6% and 1% particle volumetric concentration. Considering 1% volume fraction as an example, thermal conductivity enhancement was 18% without ball milling, rapidly increasing with ball milling time up to 27.5% for 10 hours of pretreatment. After the peak, the thermal enhancement decreases with increasing ball milling time, until it reaches the minimum point of 10.4% at 28 hours of pretreatment. More interestingly, after the enhancement shows a slight increase, reaching 12.8% at 38 hours. The authors have explained the reason behind this kind of behavior by aggregation.

2.4.3. Reasons for Enormous Thermal Conductivity Increase

The discovery of the impressive thermal performance increase of nanofluids with respect to pure fluids and classical colloidal led to the search for the reasons behind it. Several researchers tried to explain the extraordinary enhancement phenomena to investigate the deviation from the traditional understanding of energy transport in nanofluids, proposing new concepts and mechanisms behind the enhancement as well as evaluating and testing the ones proposed by other investigators. Despite the high efforts on the subject, the reason for this higher increase is still an unclear topic in the literature. There are several hypotheses on the subject, grounding the extraordinary thermal enhancement to different reasons. The most prominent theorems can be given as the ordered nanolayer of liquid molecules, the percolation theory, interfacial thermal resistance, influence of Brownian motion, nanoconvection in the suspension, surface charge model and the molecular level mechanisms of enhanced conductivity. Each hypothesis has its supporters who consider it as the dominant factor on the increase of thermal performance, and several nanofluid thermal conductivity estimation correlations and methods including the contribution of one or more of these hypotheses can be found in the literature.

2.4.3.1. Nanolayer of Liquid Molecules. The nanolayer mechanism is a well known theory to explain the enormous thermal conductivity enhancement of nanofluids as proposed by Yu and Choi [74] in 2003. The mechanism proposes a liquid layer between the nanoparticles and the base fluid, built by the base fluid molecules in the order of nano size. The layer has its own thermal conductivity higher than the one of the base fluid in comparison, and acts as a bridge between a nanoparticle and the base fluid. It is accepted that due to the effect of this layer, the thermal conductivity of the nanofluid is increased significantly. Yu and Choi developed a modified version of the Maxwell method to estimate the thermal conductivity of nanofluids including the effect of the nanolayer by the addition of a factor to estimate the thermal conductivity of the layer. They further extended the model to nanofluids with non-spherical particles by renovating the Hamilton and Crosser model.

However, the accuracy of both models failed to estimate the nonlinear behavior of the thermal conductivity enhancement. Afterwards another model taking the nanolayer effect into account was proposed by Xue [75], which also succeed to estimate the nonlinear behavior. The results for Xue's model were more accurate in terms of confirmation with experimental data. However, both Yu and Choi's and Xue's models need the nanolayer thickness and thermal conductivity assumptions for a reliable solution, therefore they encounter problems in theoretical use without experimental results.

2.4.3.2. The Percolation Theory. Percolation theory is a second hypothesis, proposed as an effective contributing factor to the thermal performance enhancement of nanofluids. The validity and effect of percolation theory is exposed more significantly in carbon nanotube fluids. In carbon nanotube fluids, extremely high aspect ratio of carbon nanofluids and addition of several nanotubes in the fluid create a conduction network and paths for heat transfer in the fluid, which increases the amount of heat transfer remarkably [3]. This type of behavior is called as percolationlike behavior [3]. Foygel *et al.* [76] has shown using Monte Carlo method that percolation starts at a very low volumetric concentration, namely 0.01%. Research shows that percolation effect causes a significant and nonlinear increase in thermal conductivity of CNT nanofluid with respect to particle concentration.

2.4.3.3. Interfacial Thermal Resistance. Huxtable *et al.* [77] used a pump-probe method is used to measure heat transfer rate across the base fluid – particle interface. They observed during the experiments an exceptionally large thermal resistance called Kapitza resistance is measured in the interface, causing a remarkable reduction in thermal conductivity. This phenomenon is later investigated by Nan *et al.* [78], and thermal conductivity enhancement model with the effect of Kapitza resistance is developed. This resistance exists in each interface, and caused by the thermal and physical difference in properties of the two media.

2.4.3.4. Brownian Motion of Nanoparticles. Previously represented static models and explanations given as the reason for the increase in nanofluid thermal conductivity are incompetent in terms of explaining the link between the temperature and thermal conductivity. Similarly, by the application of effective medium theory models, such as Maxwell-Garnett, Bruggeman and Hamilton-Crosser models the temperature and particle motion are not considered as a factor.

However, strong temperature dependence of thermal performance is an important conclusion of experimental research on nanofluids. Investigations for the reason of temperature dependence lead to the effect of Brownian motion of nanoparticles. Brownian motion is the random motion of particles in the fluid due to the collision with vibrating fluid molecules. The effect of Brownian motion is strongly related to the particle size, increasing in large amount while average particle diameter size decreases.

Xuan *et al.* [79] developed a model to predict thermal conductivity of nanofluids taking the effect of Brownian motion into account. Xuan's model predicts a direct relevance between the thermal conductivity and the square root of fluid temperature. However, several researches in the literature indicate a linear thermal conductivity increase with respect to temperature increase, declining Xuan's model.

2.4.3.5. Nano-convection. The concept of nano-convection is proposed by Jang and Choi [80] based on Brownian motion of nanofluids. The assumption behind the theory is extraordinary energy transport in the fluid due to nanoscale fluid flow around Brownian nanoparticles. The model uses the temperature dependence due to Brownian motion,

assuming that the energy transport in nanofluid by nanoscale flow of fluids around nanoparticles.

The model is initially based on Green-Kubo theorem [80], using Kapitza resistance, nanoconvection, nanoparticle size and concentration and fluid temperature as parameters to estimate the effective thermal conductivity. Later the model is improved and several similar methodical modifications have been observed by addition of multiparticle convection effects [81], specific surface area of nanoparticles [82] and kinetic theory based microconvection approach with liquid layering [83].

Despite the positive feedbacks for nano-convection, several researchers have shown negative approach to this explanation, supporting their inquiry with experimental and numerical work. Evans [84] and Vladkov [85] have shown numerically using molecular dynamics simulations that the effect of nano-convection is present but negligible for thermal performance increase. Similarly Eapen *et al.* [86] have shown that microconvection does not affect thermal conductivity of silica and Teflon nanofluid suspensions. The influence of nanoconvection in nanofluid thermal conductivity is still an unconcluded area of research in nanofluid literature, and several researchers work on the topic to reach a satisfying conclusion.

2.5. Rheology of Nanofluids

Besides the extraordinary enhancement in heat transfer, nanofluids also show different rheological properties with respect to their base fluids. Although the investigation of their rheology is not the primarily targeted topic in research on nanofluids, a comprehensive set of studies on rheological behavior of nanofluids can be found throughout the literature. The studies are concentrated on the change in fluid rheology with the addition of nanoparticles as well as the factors affecting this change in rheological behavior.

2.5.1. General behavior of Viscosity

The change in a fluids viscosity due to the loss of its purity is a well known subject in literature before the introduction of nanofluids. Recent studies show that an availability of a similar principle is also validated in nanofluids. Due to the importance in practical applications of nanofluids, their viscous behavior is a primarily focused topic today. Literature on nanofluid rheology indicates that viscosity of nanofluids differs from the viscosity of base fluids. In general nanofluids tend to have a higher viscosity with respect to their base fluids [87-92].

Several correlations have been proposed to calculate the effective viscosity (μ_m) of nanofluids as a result of practical experimental research. Long before the introduction of nanofluids, the first correlation is proposed by Albert Einstein [93] in order to calculate the viscosity of regular colloidal suspensions, by using suspended particle volumetric concentration ϕ and base fluid viscosity μ_b in order to estimate the suspension viscosity μ_m .

$$\mu_m = (1 + 2.5\phi)\mu_b \quad (2.7)$$

Einstein's formula, proposed in 1906, is the basic formulation for all colloidal suspension, and most of the later correlations are based on it. It is proven as an accurate formulation to predict the viscosity of colloidal suspensions of low concentration. However, the accuracy of the correlation decays as the particle concentration increases.

Brinkmann proposed a more accurate formulation [94] based on Einstein's correlation in 1952, providing a better consistence with experimental results for higher particle concentrations. His estimation is given below in Equation 2.8.

$$\mu_m = \frac{1}{(1 - \phi)^2} \mu_b \quad (2.8)$$

Later, in 1967 Frankel and Acrivos [95] have derivated another correlation (Equation 2.9) to approximate the suspension viscosity, using also the maximum possible volumetric

concentration of the particles in the solution. Although the method gives a sharp approximation, it has an important disadvantage. Maximum volumetric concentration $\phi_{\max}$ of particles has to be measured experimentally to use this method.

$$\mu_m = \frac{9}{8} \frac{(\phi - \phi_{\max})^{\frac{1}{3}}}{1 - (\phi - \phi_{\max})^{\frac{1}{3}}} \mu_b \quad (2.9)$$

Lundgren and Batchelor [96] have estimated the effective viscosity of a suspension by using Taylor series (Equation 2.10) in 1972.

$$\mu_m = (1 + 2.5\phi + 6.25\phi^2) \mu_b \quad (2.10)$$

The formulations given in this Section are the most known and well used correlations to estimate the viscosity. However, experimental results show that these formulations may underestimate the viscosity of nanofluids [91, 92]. Therefore, several other correlations are conducted specifically for nanofluids. Although some unrelated correlations are available in literature, most of these new proposals are mostly modified versions of Lundgren and Batchelor formulation.

2.5.2. Factors Affecting Viscosity

2.5.2.1. Particle Volumetric Concentration. Nanoparticle volumetric concentration is the primary factor affecting the change in rheological behavior of nanofluids. As it can be seen correlations above (Equations 2.1 – 2.10), each correlation is derived from base fluid viscosity and particle volumetric concentration. In literature, it is concluded that, particle concentration is a significantly important factor for the determination of viscosity, and the studies indicate that viscosity increases with increasing particle volumetric concentration [87-92].

Li *et al.* [87] observed a smaller change in viscosity due to nanoparticle volume fraction change in 2002 while studying CuO based nanofluids. Despite Li *et al.*'s results, which claim very small effect, Prasher *et al.* [88] published a study about nanofluids with

alumina particles in 2006, stating that viscosity is a strong function of particle volumetric fractions. Viscosity of the nanofluid is observed to be increased for higher nanoparticle concentrations. Prasher's results are supported by Nguyen [89] working both Al_2O_3 – water and CuO – water nanofluids with different particle sizes. Nguyen also claimed a strong dependence in particle volumetric concentration. In conclusion, the studies show increased viscosity with respect to increased particle volumetric concentration.

2.5.2.2. Particle Size. As the primary physical difference of nanofluids from regular colloidal suspensions, average size of particle is another topic investigated to determine its influence to viscosity. Several studies have been done throughout the literature to point out the effect of particle size on the viscosity of nanofluids.

Nguyen *et al.* [91] claimed a significant increase of viscosity with increasing particle size. Using Al_2O_3 nanoparticles with two different sizes; 36 nm and 47 nm, they showed that the viscosity with the same conditions is significantly higher with 47 nm particles. The experiment has been repeated for different volumetric concentrations, and the results confirmed the observation. For larger volumetric concentrations, the viscosity difference tends to increase. Similar results have been obtained by Hosseini *et al.* [92].

2.5.2.3. Change in Temperature. The effect of temperature in viscosity is widely investigated in several studies throughout the literature. The results indicate that similar to pure liquids, nanofluids possess a temperature dependent viscosity. As a general behavior the viscosity of nanofluids decreases with increasing temperature. However, whether the temperature dependence is strong or weak is still an active discussion without a universal conclusion. Several studies can be given as examples to support both arguments.

During the investigation of nanofluid viscosity, Li *et al.* [87] observed the effects of temperature on nanofluid viscosity. Using a capillary viscometer, it is shown that nanofluids containing CuO nanoparticles showed that the effective viscosity decreases with increasing Temperature. Prasher [88] observed that the viscosity of the alumina based nanofluid is not a strong function of temperature. However, the results of Nguyen *et al.* [89] indicate strong temperature dependence for Al_2O_3 – water and CuO – water

nanofluids. Nguyen also discovered the hysteresis phenomenon, which suggests that at a critical temperature the viscous behavior of nanofluids becomes drastically altered.

2.6. Research on Engine Cooling with Nanofluids

Cooling performance investigation of nanofluids for automotive engines is a brand new topic of interest in literature. Today there are a limited number of studies in literature directly pointing out cooling performance in automotive engine systems. However, with the high interest and promising results, the attention on the topic continues growing.

A comprehensive theoretical study is done by Leong [97] in 2010, who investigated thermal performance of copper – ethylene glycol nanofluids in a heat exchanger. Using a staggered heat exchanger model, and experimental thermal conductivity measurements from Eastman *et al.* [93], Leong investigated thermal performance increase of nanofluids. During the study, NTU method is used to calculate heat transfer characteristics, and thermo-physical properties of the nanofluid except for thermal conductivity have been calculated by classical correlations. Thermal conductivity of the nanofluid is directly taken from the study of Eastman *et al.* [98].

The study indicates a considerably small total heat transfer increase on the same Reynolds Number, increasing from 217.3 to 221.3 kW as it can be seen from figure 5 of Leong's study. However, he managed to reach a total frontal area decrease of 18.77% for air side Reynolds number of 6000 and liquid side Reynolds number of 5000.

His results have been verified by the same calculations through this study. However, the extraordinary increase is the result of very sharp thermal conductivity increase of nanofluids. Figure 1 of Leong's paper shows an incredibly strong thermal conductivity increase due to particle concentration, which is about 375% higher for the nanofluid with 2% volumetric concentration with respect to pure ethylene glycol. Such an increase is unable to be predicted by current thermal conductivity models and correlations. With the thermal conductivity estimation results from Maxwell correlation (Equation 2.1), thermal performance increase drops to very low levels. Verification of the calculation method by calculating Leong's results is done and presented in Appendix B.

In 2007 Saripella *et al.* [99] used CuO nanoparticle containing nanofluid in truck engines to evaluate nanoparticle effects. They used 50% water – 50% ethylene glycol as the base fluid, and evaluated the temperature distribution for volumetric particle concentrations of 2% and 4%. Comparing the results to initial base fluid results, decreased engine and coolant temperatures have been observed. Their results showed a potential for up to 5% air side surface area reductions.

Nguyen *et al.* [100] worked on nanofluids for submerged impinging jet experimentally, using Al_2O_3 nanoparticles for a wide scale of Reynolds number from 3800 to 88000. The nanoparticles had an average diameter of 36 nm, and the volumetric concentration varied from 0% to 6%. Through the study contradicting results have been obtained, where in several cases nanofluids provided very good thermal performance enhancement, and in several cases did not increase the heat transfer. Some of the results have shown heat transfer decrease with the addition of nanoparticles. The highest thermal performance enhancement has been observed at 2.8% volumetric concentration of nanoparticles.

Duangthongsuk and Wongwises [101] studied a counterflow heat exchanger for TiO_2 nanofluid to examine the thermal performance increase. However, they have used constant temperature boundary condition and a single nanoparticle volumetric concentration (0.2%), leaving the flow Reynolds number as the only variable. They have found that the experimental Nusselt number exceeded the theoretical Nusselt number value, and increased almost linearly with increasing Reynolds number. They also concluded that pressure drop increases significantly for high Reynolds numbers.

2.7. Research on Boron Nitride Nanofluids

Despite the promising physical properties of boron nitride, only a limited number of studies are available on their use as nanoparticles. One example is Sleiti's study [102] on rheological behavior of hexagonal boron nitride and polyalpha-olein oil containing nanofluids. He studied nanofluids with particle volumetric concentrations of 0.25%, 0.6% and 1%, and evaluated the viscosity change in a wide range of temperature. Sleiti's results indicate an increase in viscosity with respect to increasing particle volumetric

concentration as expected. Another conclusion of the study is specified as the decrease of viscosity with increasing temperature.

Another study on boron nitride containing nanofluids was fulfilled by Li *et al.* [103]. They have investigated nanofluids consisting of boron nitride and ethylene glycol in various volumetric concentrations up to 5.5%. During the studies two set of nanofluids have been prepared. The difference between the sets is defined as the change in average particle size. In one set of nanofluids, nanoparticles with an average particle diameter of 70 nm are used, whereas in the second set average particle diameter of nanoparticles is 140 nm. The results indicate a linear increase in thermal conductivity with increasing particle volumetric concentration, indicating a maximum thermal conductivity enhancement of 25% for 70 nm nanoparticles and 30% for 140 nm particles at 5.5% volumetric concentration. Another Higher thermal conductivity enhancement for larger nanoparticle size is underlined as an abnormal phenomenon. However, it should be noted that during the study the type of boron nitride is not given. Considering the phenomenon and the commercial availability of boron nitride nanoparticles, the probability of using two different boron nitride types during the study exists. Due to its superior thermal and physical properties, it is possible to have a higher enhancement using cubic boron nitride despite the increase in particle size.

3. MODEL VERIFICATION FOR NUMERICAL ANALYSIS

3.1. Numerical Flow Modeling

3.1.1. Single Phase and Two Phase Methods

Two options are available for numerical studies simulating flow and thermal performance of nanofluids: single phase modeling and two phase modeling. In single phase method, the nanofluid is considered as a single fluid, where effective properties calculated by correlations are used as fluid properties. This method is more effective in terms of time and computation power, but may contain a slight accuracy loss due to correlation error factors, and deviations of experimental results from correlations. However, most studies in literature use single step method to calculate thermal performance of nanofluids.

In two phase method the base fluid and particles are modeled separately and their interactions with each other are also taken into account. This method gives more accurate results. Moreover this method needs significantly more time and computation power with respect to single phase method.

In this study, the first method is used for numerical analysis. The nanofluid is considered as a single phase fluid, whose thermal and physical properties are accepted as effective properties, and assumed constant among the whole fluid. The calculation of these parameters by correlations is given in Section 3.2.

3.1.2. Modeling Software

In this study, a commercial computational fluid dynamics software Ansys Fluent is used for numerical simulations. Fluent relies finite volume method to solve the governing equations to simulate the flow. Geometry drawing, meshing, calculations and post processing are fulfilled by various Ansys Workbench applications.

3.1.3. Governing Equations

The governing equations to define the flow are the continuity equation, the momentum equation and the energy equation. Several assumptions are made for the simulation. It is accepted that no body forces are acting on the flow. Due to the steady state flow, the continuity equation is simplified as below in Equation 3.1.

$$\nabla \cdot (\rho \vec{v}) = 0 \quad (3.1)$$

The general formulation for conservation of momentum in an inertial non-accelerating frame is given in Equation 3.2.

$$\nabla \cdot (\rho \vec{v} \vec{v}) = -\nabla p + \nabla \cdot (\bar{\tau}) \quad (3.2)$$

In Equation 3.2, $\bar{\tau}$ is the stress tensor, and p is the pressure. The definition of stress tensor is given below in Equation 3.3 with I being the unit tensor.

$$\bar{\tau} = \mu \left[(\nabla \vec{v} + \nabla \vec{v}^T) - \frac{2}{3} \nabla \cdot \vec{v} I \right] \quad (3.3)$$

For an incompressible flow without dissipation and heat generation, the general energy equation used in the analysis is following:

$$\rho c_p \frac{DT}{dt} = -(\nabla \cdot \vec{q}) \quad (3.4)$$

where T is the temperature and D/Dt represents the material derivative. The heat flux vector $\vec{q}$ is defined according to Fourier's Law (Equation 3.5).

$$\vec{q} = -k \nabla T \quad (3.5)$$

The numerical analyses in this study are conducted to simulate the flow behavior in turbulent regime. There are several options to model turbulence numerically. Most

common models are k - ϵ and k - ω models, which take the kinetic energy, dissipation rate and specific dissipation rate into account in order to calculate turbulence. Standard and shear-stress transport (SST) k - ω models are used throughout the simulations to achieve better accuracy. Detailed explanations of these models are given in Appendix A. In circular pipes, standard k - ω model is used throughout the simulations, whereas SST k - ω is preferred for radiator analyses.

Standard k - ω model is based on Wilcox k - ω model [104], which incorporates modifications for low-Reynolds-number effects, compressibility and shear flow spreading. Standard k - ω model uses equations for turbulent kinetic energy and specific dissipation rate to predict turbulence.

Shear-Stress Transport (SST) k - ω model is developed by Menter [105], using k - ω model in near wall regions and k - ϵ model at regions far from the wall. It uses a blending function to transform k - ω to k - ϵ .

3.2. Nanofluid Property Estimations

Several methods have been proposed to predict the thermal and rheological properties of nanofluids. The most commonly used methods and correlations have been given in Chapter 2. The general density formulation for colloidal suspensions is used to calculate the nanofluid density.

$$\rho_m = \phi \rho_p + (1 - \phi) \rho_b \quad (3.6)$$

As proposed in Section 2.5.1, various correlations are available in literature to calculate the effective viscosity of colloidal suspensions. However, as specified and shown in that section, nanofluids show different characteristics with respect to classical colloidal suspensions. Various modifications of Brinkmann's (Equation 2.8) and Lundgren & Batchelor's (Equation 2.10) correlations are proposed to estimate the viscosity of nanofluid. The viscosity of nanofluids with Al_2O_3 and hBN are calculated in this study by using a modified version of Lundgren & Batchelor correlation [89]. The method is tested to calculate the effective viscosity for sample data from the literature and has shown good

confirmation with experimental data for Al_2O_3 – water nanofluids. The results can be seen in Figure 3.1, where Lundgren & Batchelor Equation is presented as Batchelor Formula.

$$\mu_m = (1 + 7.3 \phi + 123 \phi^2) \mu_b \quad (3.7)$$

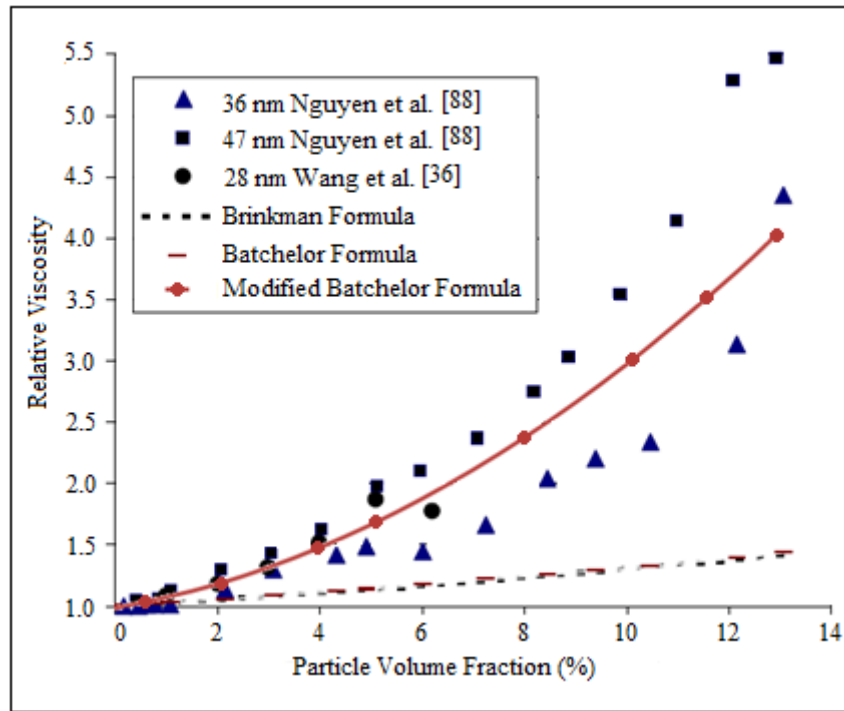


Figure 3.1. Comparison of various models with experimental data.

Several methods and correlations are available in the literature to predict the thermal conductivity of nanofluids, and new correlations are proposed occasionally. None of these methods are accepted method to calculate thermal conductivity. However, a few correlations are used very frequently. Among the frequently used correlations (Equations 2.1 – 2.6), Maxwell and Bruggeman correlations give almost the same results for nanoparticle concentration range of this study, Hamilton & Crosser formula reduces to Maxwell equation if spherical particle shape is chosen, Xue model is for carbon nanotubes instead of spherical particles and Yu & Choi model requires unknown nanolayer properties, which can only be obtained from experimental results, which are not present for hexagonal boron nitride nanoparticles. Beyond these general formulations, particle material specific correlations are also present in literature. However, limited study exists

about boron nitride, therefore the validity and constant values of these correlations are also unknown. Besides this knowledge; although there are several examples concluding that Maxwell equation underestimates the thermal conductivity enhancement of nanofluids [29, 81, 98], it is presented in Section 2.4.2 that thermal conductivity enhancement of nanofluids is decreased with increasing particle size, and hexagonal boron nitride nanoparticles are commercially available only for an average particle size above 70 nm. Considering these facts, as one of the most used correlations, Maxwell's formula will be used to predict thermal conductivity of nanofluids in this study (Equation 2.1).

Specific heat capacity of the nanofluid $c_{p,m}$ is estimated by using the average volume fraction formulation:

$$c_{p,m} = \frac{\phi \rho_b c_{p,b} + (1-\phi) \rho_p c_{p,p}}{\rho_m} \quad (3.8)$$

In this study various nanofluids will be used for numerical analysis. In Chapter 3, model verification will be done with diamond – water and TiO_2 – water nanofluids in various concentrations. Chapter 4 will concentrate on general behavior of hBN – water nanofluids. Thermal and physical properties for those materials are given in Table 3.1.

Table 3.1. Thermo-physical Properties used in cylindrical tube analyses.

	Water (293 K)	Water (300 K)	Diamond	TiO_2	hBN
ρ [kg/m ³]	997.78	996.05	3530	4230	2200
k [W/mK]	0.60475	0.61519	1500	11.7	600 / 30
c_p [J kg/K]	4076.4	4051.6	509.1	170	739.8
μ [W/m ² K]	0.000977	0.00083	-	-	-

In Chapter 5, water and ethylene glycol mixture will be used as the base fluid instead of pure water. Nanofluids with various concentrations of Al_2O_3 and hBN will be used. Properties for those materials are available in Table 3.2. These properties are used for the numerical analysis to simulate the thermal behavior of hBN / water nanofluid in the

cylindrical tube as well as in the car radiator. The compliance of the formulation results with experimental measurements is interpreted in the section for validation of experimental results in literature.

Table 3.2. Thermo-physical Properties used in radiator analyses.

	Water-EG (50%-50%, 367K)	Al ₂ O ₃	hBN	Air	Aluminum
ρ [kg/m ³]	1016	3950	2200	1.225	2719
k [W/mK]	0.4719	46	600 / 30	0.0242	202.4
c_p [J kg/K]	3457.9	880	739.8	1006.43	871
μ [W/m ² K]	0.000647	-	-	1.79E-05	-

It is a known fact that hexagonal boron nitride is an orthotropic material with layered structure. The thermal conductivity is 600 W/mK along the layers, and 30 W/mK through the layers. As given in Table 3.2, during the numerical calculations arithmetic mean value of both directions, 315 W/mK is used for thermal conductivity. This approximation gives consistent results with Ohmura *et al.*'s [106] measurements for materials with directional thermal conductivities. Among other approximations tried in this study, this method has shown highest accuracy to predict experimental results.

3.3. Verification and Optimization of the Numerical Structure

A grid independence study has been carried out. The same simulation with the same initial and boundary conditions is run at each analysis, and numerical results are compared with theoretical or experimental results extracted from literature. The results within an reasonable error range are selected as candidates, and the one with lowest computational time and effort is chosen. A turbulent flow case with pure water, having the properties of $\rho = 998.2$ kg/m³, $c_p = 4182$ J kg/K, $k = 0.6$ W/mK and $\mu = 0.001003$ W/m²K with a constant inlet velocity of 0.86 m/s is chosen for this study. From these values, Reynolds number (Equation 3.9) of the fluid is calculated as 6850.

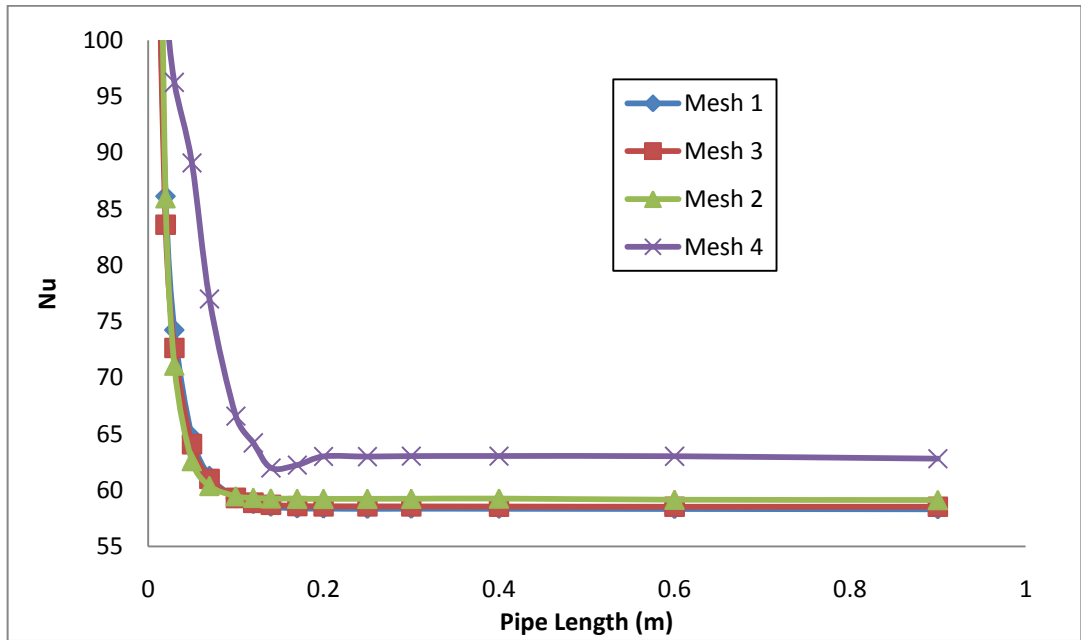


Figure 3.2. Results of different meshes.

This process is accomplished throughout the analysis for each geometrical setup in consideration. As an example, pure water flow results with 4 different meshes are given in Figure 3.2. The flow is a turbulent flow in a cylindrical tube with 8 mm diameter and 1 m length. Mesh 1 has 1399452 nodes, mesh 2 has 127200 nodes, mesh 3 has 26765 nodes and mesh 4 has 1029 nodes. Nusselt number (Equation 3.10) of the flow is calculated for each mesh, and the results are compared with Dittus-Boelter correlation (Equation 3.11), which gives a Nusselt number of 58.04 for this setup. The variable n in Equation 3.11 takes the value 0.4 for heating the fluid and 0.3 for cooling the fluid.

$$Re = \frac{\rho v D_h}{\mu} \quad (3.9)$$

$$Nu = \frac{h D_h}{k_m} \quad (3.10)$$

$$Nu = 0.023 Re^{0.8} Pr^n \quad (3.11)$$

$$Pr = \frac{\mu c_p}{k} \quad (3.12)$$

The analysis is performed with grids having 127200 nodes as given in Section 3.3. Reynolds number of the nanofluid is defined in Equation 3.9. D_h is the hydraulic diameter of the flow geometry, and for cylindrical pipes it is equivalent to the pipe diameter. The symbol “v” represents average flow velocity. For each analysis in this validation and further simulation in this study nanofluid properties will be used in calculation of Reynolds (Equation 3.9) and Nusselt (Equation 3.10) numbers. To calculate these numbers, nanofluid effective properties and Prandtl number (Equation 3.12) are used for each concentration.

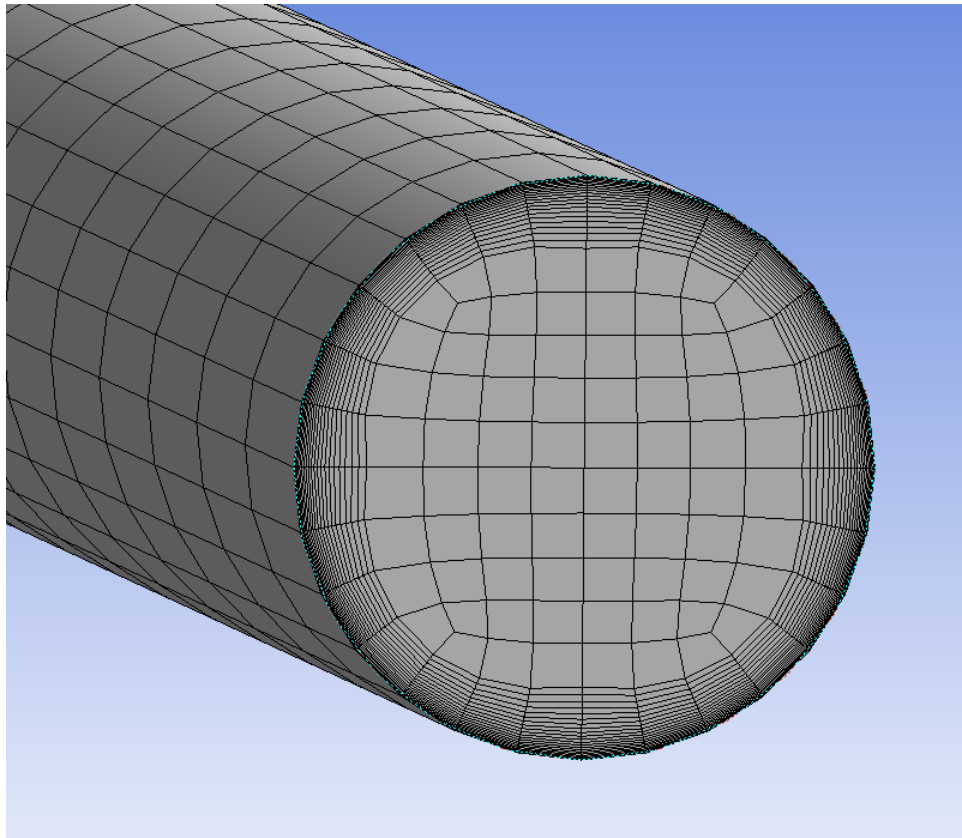


Figure 3.3. Screenshot for the mesh used in analysis.

The meshes 1, 2, 3 and 4 in consideration have calculated Nu value as 58.37, 58.54, 59.14 and 63 respectively. Results for several other meshes are also investigated before

choosing the proper mesh. Evaluating different mesh possibilities, mesh 2 with 127200 is chosen for further analysis to satisfy both factors of accuracy and computational time. The analyses in Chapter 3 and Chapter 4 are accomplished using this mesh. A picture of mesh 2 is presented in Figure 3.3.

3.4. Validation of Experimental Results in Literature

3.4.1. Validation with Diamond – Water Nanofluid

To validate the numerical analysis and confirm the accuracy, sample experimental results have been simulated to compare the results. The experimental study of Torii *et al.* [107] has been chosen for initial validation. They have investigated the thermal performance of a nanofluid consisting of water and diamond nanoparticles experimentally. The nanofluid is evaluated in a horizontal cylindrical tube system with constant heat flux heating. In the study, the thermal properties of the nanofluid are measured experimentally. Therefore, it is also possible to avoid the deviations due to the nanofluid property correlations. Moreover, the effect of estimating the nanofluid properties by correlations and the deviation due can be estimated by repeating the numerical work with both experimental and correlation-found properties.

The heat transfer coefficient of the fluid h is calculated from Newton's law of cooling presented in Equation 3.13, where T_s is the surface temperature and T_b is the mean temperature of the fluid. T_s and T_b values are taken from numerical results in different cross sections of the pipe.

$$Q = h A (T_s - T_b) \quad (3.13)$$

Experimental results of the study for diamond nanoparticle concentration of 0.1% are simulated numerically, and the comparison of numerical results with experimental Nusselt number results from measured properties can be seen in Figure 3.4.

It is observed that the numerical model is in good agreement with experimental data, having a maximum deviation of 1.3%. Despite the good results, the validity of the model is

further investigated for a different nanofluid in different operating conditions in the following section.

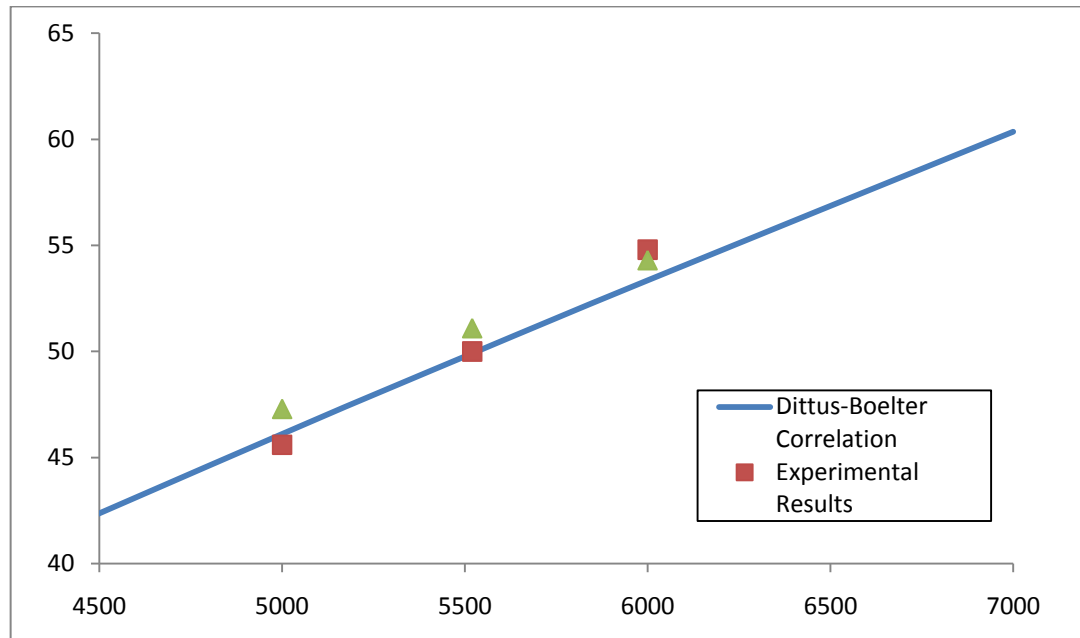


Figure 3.4. Experimental data vs. numerical approximation.

3.4.2. Validation with TiO_2 – Water Nanofluid

Further validation is carried out to simulate the experimental results of Kayhani *et al.* [108] for TiO_2 – water nanofluids. They studied nanofluids with TiO_2 particles in a circular cylinder subjected to constant surface heat flux under turbulent regime in a wide range of Reynolds numbers from 7000 to 15000.

Their experimental results show an increase in Nusselt number by increasing particle concentration. Numerical simulation presented in Figure 3.4 and 3.5 shows a similar trend with a small deviation. It is observed that within the small margin of error numerical results overestimate experimental results in small particle volumetric concentrations, and underestimate in higher concentrations. Two different sets of data have chosen from the experimental results, one around the Reynolds number of 9500 and one around the Reynolds number of 12000. The results show very good agreement with experimental

results, with a maximum deviation of 3.57% at the second data set with 2.0% particle volumetric concentration. These results confirm the validity of numerical model.

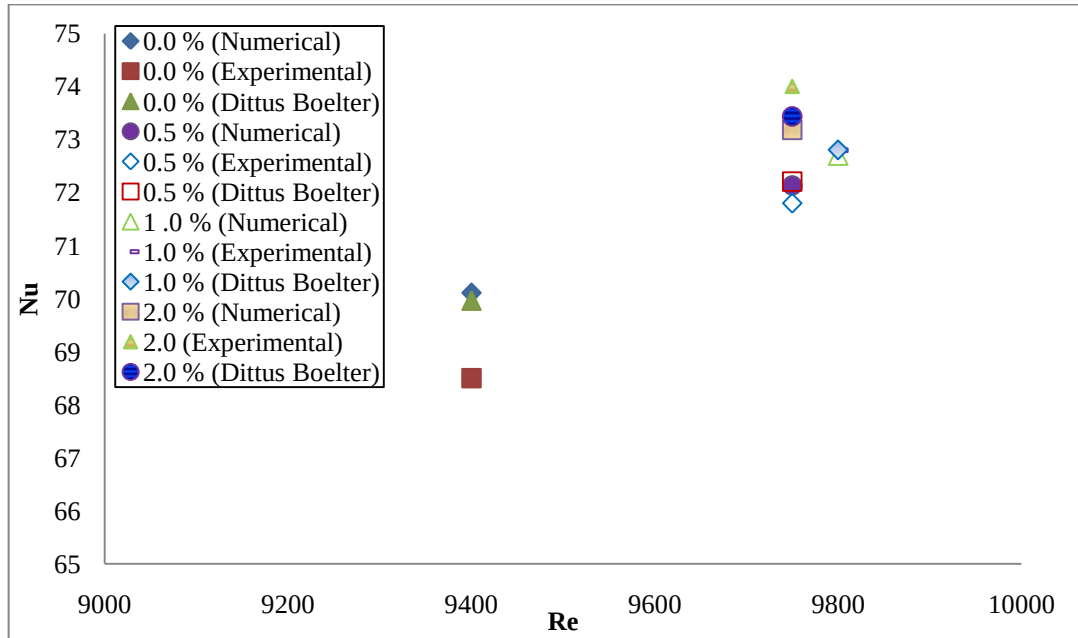


Figure 3.5. Comparison of Nu for 0.0%, 0.5%, 1.0% and 2.0% for first data set.

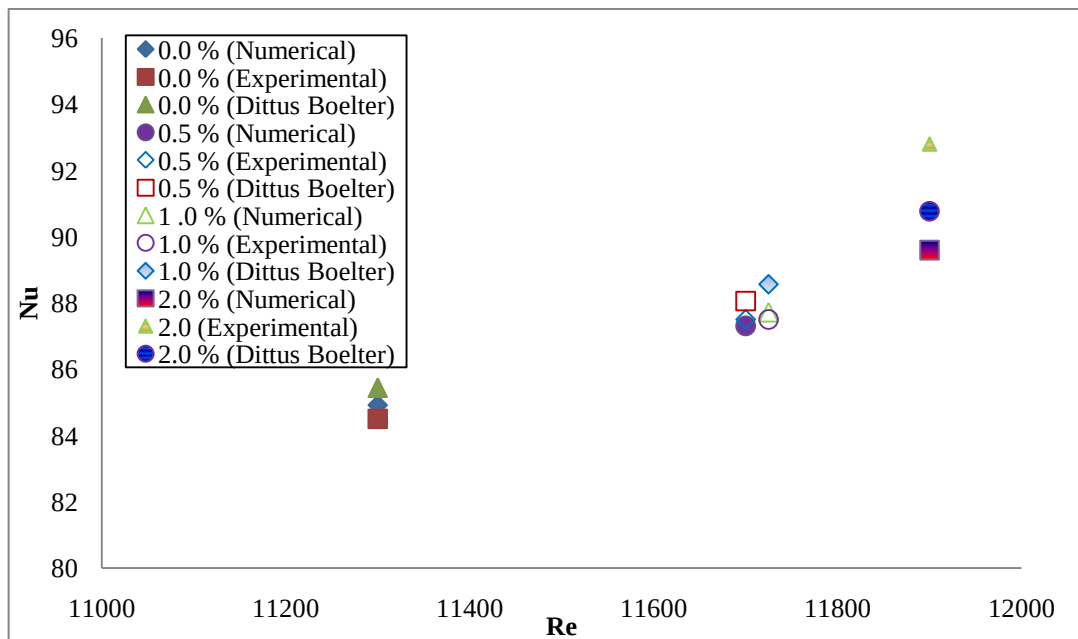


Figure 3.6. Comparison of Nu for 0.0%, 0.5%, 1.0% and 2.0% for second data set.

Another observation of this chapter is that Dittus-Boelter correlation is also in good agreement with experimental results. However, it should be noted that these experiments have been done in cylindrical tube, a symmetrical and simple geometry in which Dittus-Boelter correlation generally predicts thermal properties with very good accuracy.

4. CYLINDRICAL TUBE ANALYSIS FOR hBN – WATER NANOFLUID

One important purpose of this study is the analysis of hexagonal boron nitride containing nanofluids and their behavior. As explained in Section 1.4, hBN is a very promising candidate to be used as nanoparticle for higher thermal performance enhancement of nanofluids. Therefore, it is chosen as one of the materials to be simulated in radiator analysis. However, Lack of knowledge about hBN containing nanofluids led to a preliminary general analysis for hBN – water nanofluid in order to examine the contribution of hBN nanoparticles in general thermal performance.

4.1. Problem Statement

General performance analysis of hBN containing nanofluids is done in cylindrical tube geometry with diameter of 8 mm and length of 1 m. The accuracy of the numerical model for this geometry has been validated with diamond and TiO₂ nanofluids in previous chapter.

Hexagonal boron nitride – water nanofluid with various volumetric concentrations has been tested for thermal performance enhancements. Thermal and rheological properties of the hBN / water nanofluid are estimated by using the correlations presented in Section 3.1.

Cylindrical pipe is subjected to a uniform heat flux of 200000 W/m². Various particle volumetric concentrations are investigated on Reynolds number of 6000 and 10000 in order to evaluate the change in thermal behavior of hBN nanofluid with respect to volumetric concentration change. During the numerical investigation, inlet flow velocity for these Reynolds numbers are calculated from Equation 3.9. Choosing turbulent flows with selected Reynolds numbers, Nusselt number and heat transfer coefficient of nanofluids are investigated.

4.2. Results and Discussions

As expected, numerical modeling has shown similar results to Dittus-Boelter correlation. It has been noticed that Nusselt number of the fluid increases both with volumetric concentration and Reynolds number. The increase with Reynolds number did not show any special or different results from expected improvement due to flow velocity increase.

Nusselt number has increased by 8.9% when the hexagonal boron nitride nanoparticle volumetric concentration increased to 5% from 0% in flows of the Reynolds number of 6000. The enhancement observed in 10000 Reynolds number is comparably higher, 9.2% (Figure 4.1). In comparison, a higher heat transfer coefficient increase is observed in both Reynolds numbers (Figure 4.2) according to the numerical results.

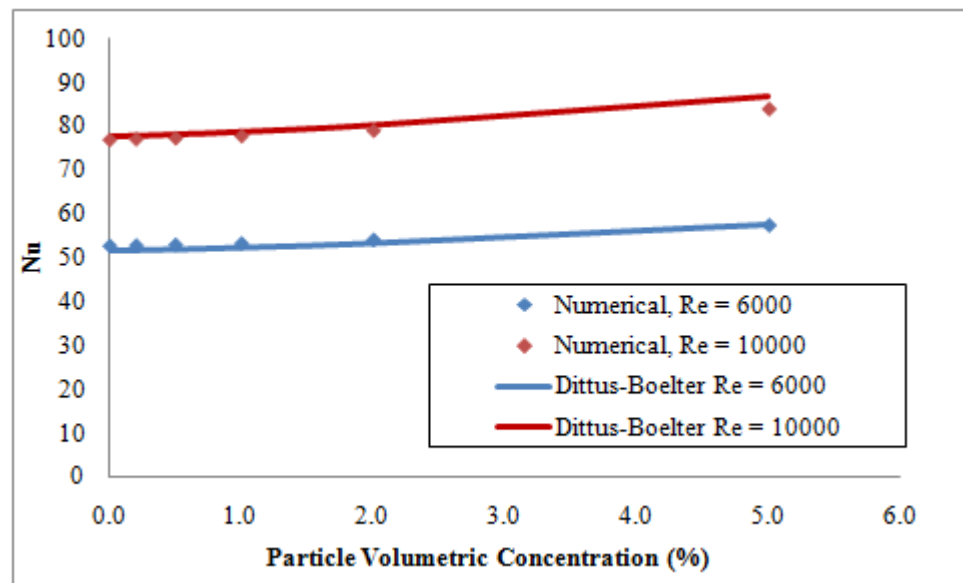


Figure 4.1. Nusselt Number increase for hBN – Water nanofluids.

It should be noted that the thermal conductivity of the nanofluid increases with increasing nanoparticle fraction. By definition, thermal conductivity and Nusselt number are inversely proportional (Equation 3.10). However an increase both in thermal conductivity and Nusselt number is observed (Figure 4.1 and Figure 4.2) due to a more

significant heat transfer coefficient increase. Numerical results indicate that the heat transfer coefficient of the nanofluid increased significantly higher with respect to thermal conductivity, having an improvement of 26% for Reynolds number of 6000 and 26.3% for Reynolds number of 10000 as the particle concentration increases from 0 to 5%.

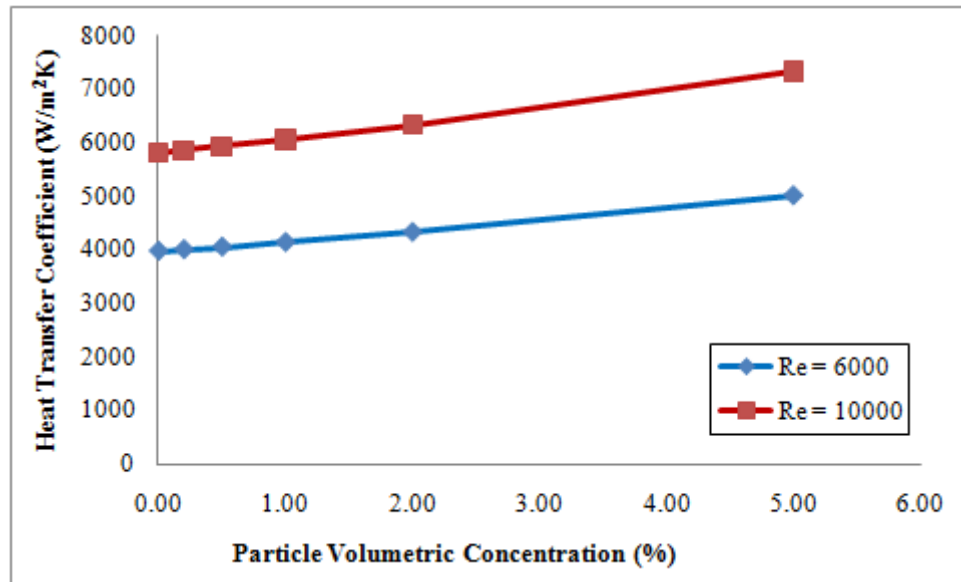


Figure 4.2. Heat transfer coefficient increase for hBN – Water nanofluids.

Hexagonal boron nitride is significantly superior with respect to other nanoparticle materials. In comparison with alumina, diamond and titanium dioxide, hexagonal boron nitride shows considerably better increase both in Nusselt number (Figure 4.3) and heat transfer coefficient (Figure 4.4), reaching the values of 86.7 and 7578.2 W/m²K respectively for 5% particle fraction and Reynolds number of 10000. Among these results, hBN's superiority to diamond despite its lower thermal conductivity in comparison is an important observation. This result is due to significantly low specific heat capacity and higher density of diamond.

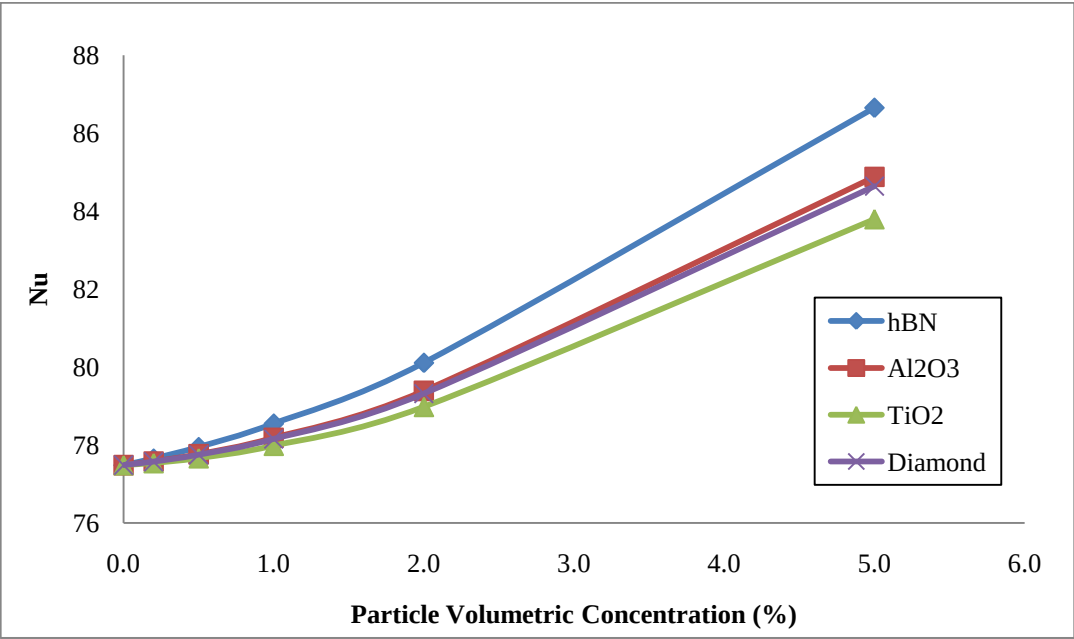


Figure 4.3. Nusselt number comparison.

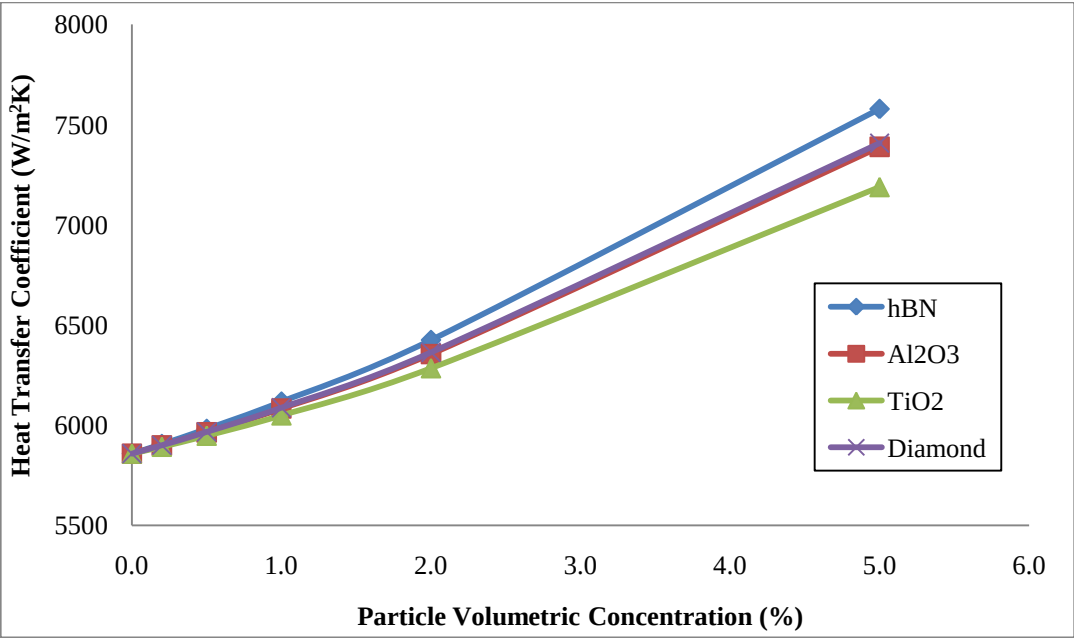


Figure 4.4. Heat transfer coefficient comparison.

5. ENGINE COOLING SYSTEM ANALYSIS

5.1. Thermal Performance Calculations for the Radiator

In this chapter, cooling performance of nanofluids will be investigated for their suitability as engine coolants. Numerical and theoretical calculations will be carried out to evaluate the thermal enhancement of nanofluids, on different volumetric concentrations, boundary conditions, and radiator geometries in order to determine the performance enhancement, limitations and benefits. Nanofluids consisting of 50% water – 50% ethylene glycol as base fluid, and Al_2O_3 and hBN as nanoparticles with volumetric concentrations of 0.2%, 0.5%, 1.0%, 2.0% and 5.0% are investigated throughout the analysis. Throughout the study, besides different particle volumetric concentrations of nanofluids, also various air heat transfer coefficients in a range of 56.27 - 300 $\text{W/m}^2\text{K}$ are investigated. The aim of the study is to determine the thermal performance of nanofluids having hBN as nanoparticle, and to compare their performance to a more common and well known material of Al_2O_3 .

An aluminum internal combustion engine cooling system radiator with core dimensions of 694.5 x 462 x 25 mm is chosen for the performance analysis. The radiator has 28 tubes with cross section dimensions of 1.5 x 25 mm. 620 fins, assumed rectangular due to simplicity, with dimensions of 15 x 25 mm and 0.12 mm thickness are used between tubes. The radiator is a single pass radiator with continuous parallel liquid tubes and perpendicular air channels in between, separated from each other by fins. The radiator is designed with proper size for a large sized passenger car.

To simplify the calculation process a single tube of the radiator is modeled for the analysis. The upper and lower walls of the tube are to be subjected to efficient heat transfer coefficient boundary condition, whereas the side walls are considered as adiabatic. Overall radiator results are estimated from the single tube analysis. The explanation of the calculations are provided page 68. Sketches for the radiator type and modeled tube are presented in Figure 5.1 and Figure 5.2 respectively. A sample radiator is presented in Figure 5.3.

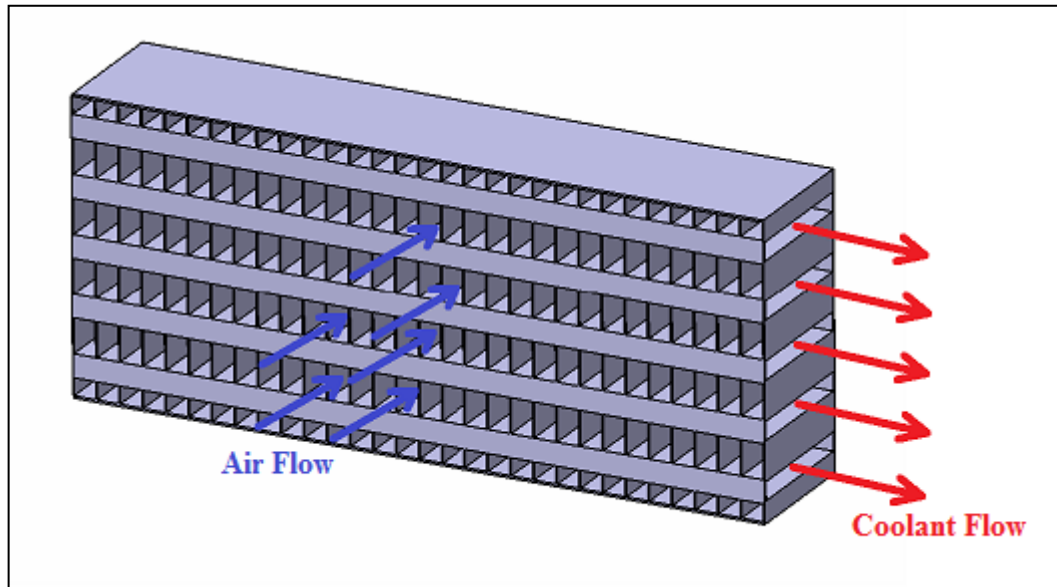


Figure 5.1. Radiator geometry.

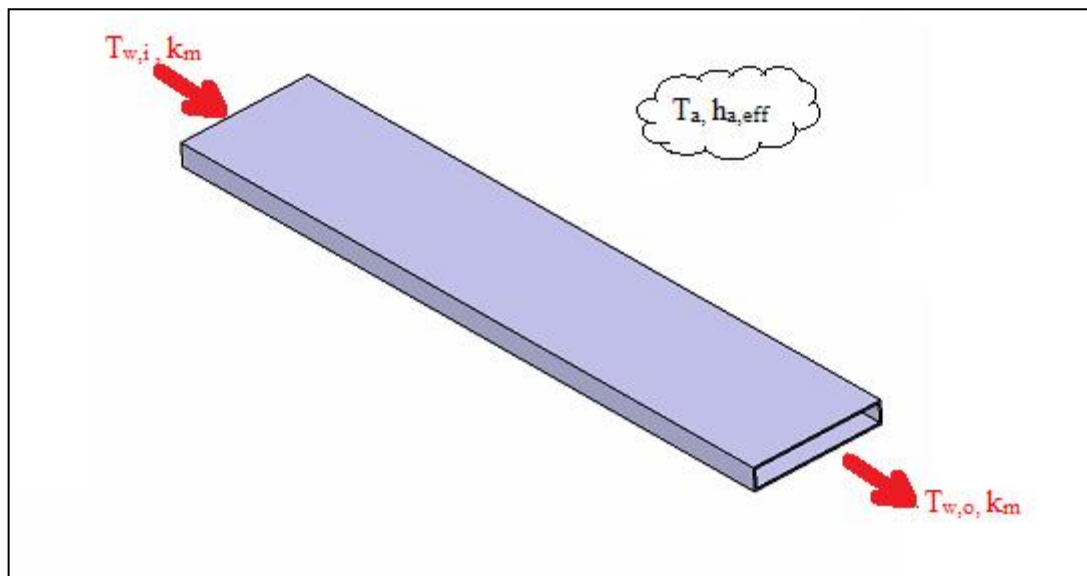


Figure 5.2. Radiator tube (modeled part).

The symbol N in Figure 5.1 represents the number of tubes, $T_{w,i}$ and $T_{w,o}$ in Figure 5.2 are inlet and outlet temperatures of the liquid in the tube, T_a is the mean air temperature, and $h_{a,eff}$ is the effective air heat transfer coefficient.

Air and water properties are used as given in Table 3.2 in Section 3.2, taken from literature. Thermal and physical properties of 50%-50% water - EG base fluid in 367 K are taken from Waterloo University web site [109]. Hexagonal boron nitride properties are taken from literature. Air and liquid inlet temperatures are chosen as 293 K and 370 K respectively. Necessary thermal and physical properties of nanofluids for hBN and alumina are obtained from calculations given in Section 3.5.



Figure 5.3. Sample automotive radiator. [110]

The analysis is carried out for a coolant Reynolds number of 6500. Various air approach velocities are considered in a range of 4 m/s to 41.8 m/s. From the calculations for air channel geometry, air side Reynolds number is calculated as 632.45 for air approach velocity of 4 m/s, which indicates a laminar air flow. Therefore, air side Nusselt number is considered as 4.36 by to simplify the flow by the assumption of constant heat flux boundary condition for laminar flow. For other values in turbulent regime, Dittus-Boelter correlation is used to calculate the Nusselt number.

Air and liquid side outlet temperatures as well as the total cooling load are calculated by Number of transfer units and effectiveness (NTU- ϵ) method for cross flow single pass heat exchangers with unmixed flow conditions. The cooling load for this method is defined as

$$Q = \epsilon C_{\min}(T_{w,i} - T_{a,i}) \quad (5.1)$$

and the effectiveness ε of the heat exchanger is defined as

$$\varepsilon = 1 - \exp\left[\frac{1}{C_r}\right] (NTU)^{0.22} [\exp[-C_r(NTU)^{0.78}] - 1] \quad (5.2)$$

The effectiveness is defined in terms of number of units (NTU), which is calculated by the following equation

$$NTU = \frac{UA}{C_{\min}} \quad (5.3)$$

C_r in Equation 5.2 is the ratio of minimum and maximum heat capacities for both fluids in heat exchanger. These values are calculated from the densities and specific heat capacities of the fluids.

$$C_r = \frac{C_{\min}}{C_{\max}} \quad (5.4)$$

$$C_{\min} = \min[C_a, C_w] \quad (5.5)$$

$$C_{\max} = \max[C_a, C_w] \quad (5.6)$$

$$C_a = \rho_a c_{p,a} \quad (5.7)$$

$$C_w = \rho_w c_{p,w} \quad (5.8)$$

where ρ_a and ρ_w are densities of air and liquid respectively, and $c_{p,a}$ and $c_{p,w}$ are specific heat capacities of air and liquid respectively.

The result is afterwards verified for the liquid side of the radiator numerically. One tube of the radiator is modeled and meshed and the fluid behavior is observed. Side walls of the tube are considered as adiabatic boundary condition. Upper and lower walls are subjected to effective heat transfer coefficient to consider the effect of heat transfer effect

of the fins. The properties are used for the mean air inlet and outlet temperatures. Effective heat transfer coefficient of air is achieved by using previously calculated air side heat transfer coefficient, finned (A_{tot}) and unfinned (A_u) and base (A_b) wall areas and fin efficiency.

$$h_{a,eff} = \frac{\eta_0 A_{tot}}{A_u} h_a \quad (5.9)$$

$$A_{tot} = A_b + N_f A_f \quad (5.10)$$

Overall surface efficiency for Equation 5.9 and Equation 5.10 is calculated from Equations 5.10-12 [111]

$$\eta_0 = 1 - \frac{N_f A_f}{A_{tot}} (1 - \eta_f) \quad (5.11)$$

$$\eta_f = \frac{\tanh(m L_f)}{m L_f} \quad (5.12)$$

$$m = \sqrt{\frac{2 h_a}{k_f t_f}} \quad (5.13)$$

where N_f is number of fins, A_{tot} total Area, A_b is base area, η_f is fin efficiency and η_0 is overall surface efficiency. L_t is the length of the fin, t_f is thickness of the fin and h_a is the heat transfer coefficient of air. Liquid side heat transfer coefficient is taken from the definition of Nusselt number (Equation 3.10), whereas the Nusselt number is estimated by Dittus-Boelter correlation (Equation 3.11). The value of n is taken as 0.3 due to the heat removal process.

The heat exchanger consists of parallel heat transfer paths. From the analyzed single tube, the overall heat transfer is approximated by using overall heat transfer coefficient (Equation 5.14).

$$\frac{1}{UA} = \frac{1}{\eta_0 A_{\text{tot}} h_a} + \frac{1}{A_b h_w} \quad (5.14)$$

Due to the high aspect ratio of fluid channel (aspect ratio: 1:16.67) and adiabatic boundary conditions on side walls, hydraulic diameter is approximated by considering the problem as a flow between parallel plates. After the initial analysis for calculated air side heat transfer coefficient, different air side boundary conditions are also investigated to cover different environmental conditions. The possibility of increasing air side heat transfer coefficient and/or air inlet velocity is taken into account. Therefore, besides the air side initial heat transfer coefficient as 56.27 W/m²K, higher heat transfer coefficients are used. Air heat transfer coefficients of 100, 200 and 300 W/m²K are selected to evaluate the effect of boundary conditions, and the changes with respect to different boundary conditions are pointed out. For the radiator geometry in consideration the related air approach velocities for these boundary conditions are 10.7, 25.2 and 41.8 m/s respectively.

As a final evaluation, the effect of the radiator geometry is investigated. Radiator dimensions have been changed to increase the frontal area, keeping the aspect ratio constant. Thermal performance of Al₂O₃ and hBN nanofluids are investigated with various sizes.

5.2. Evaluation of Results

5.2.1. Theoretical Calculation Results

Before the analysis has been accomplished, theoretical calculations of Leong *et al.* [97] have been reproduced with the methods provided from the author throughout the article, and the extraordinary heat transfer enhancement is confirmed. The results indicate a frontal area reduction of more than 18% for the copper – ethylene glycol nanofluid. Leong's results have been recalculated in Appendix B and similar results have been obtained as a confirmation for the validity of the calculation method in this study. However, it is noted that Leong uses experimental data set from Eastman *et al.* [98] for the thermal conductivity of his nanofluid.

This data set used by Leong shows an anomalous increase in thermal conductivity with the addition of nanoparticles, reaching an increase of more than 275% for 2% copper nanoparticle volumetric concentration. Observed thermal conductivity increase is excessively higher than predictions of any thermal conductivity estimation correlation used commonly in literature. To illustrate, thermal conductivity increase calculated by Maxwell correlation gives only %6.2 enhancement for the same conditions. The selection of base fluid as ethylene glycol, having a poor thermal conductivity with respect to water and water – ethylene glycol mixtures may be noted as one reason for this anomalous enhancement. However, the main reason for this spectacular thermal conductivity increase is predicted as the significantly small size of particles (10 nm). The effect of particle size to thermal conductivity increase is more deeply evaluated in Section 2.4.2.2. This anomalous thermal conductivity increase affects the results of Leong's analysis strongly in positive direction.

However, due to the introduction of the new material of hexagonal boron nitride, and lack of experimental data set respectively, it is not possible to reach such high enhancements by a general correlative method. Besides, recent survey indicates that hBN is not found in nanoparticle form with diameter smaller than 70 nm. Consideration of these facts and the reasons given in Section 3.2 led to Maxwell correlation in this study. Therefore, the thermal performance increase is expected to be considerably lower with respect to Leong's results.

As a second step, the boundary conditions of the radiator geometry are calculated. Using theoretical calculations given in previous section, Reynolds number of air is calculated as 632.45 for the given radiator geometry with an air inlet velocity of 4 m/s, indicating laminar flow regime for air. It is observed that air side heat transfer coefficient is 56.27 W/m²K respectively. Nusselt numbers of Al₂O₃ and hBN nanofluids (Figure 5.4) are calculated by using Dittus–Boelter correlation for the given boundary condition, and applying necessary correction for rectangular ducts as given in the Handbook of Rohsenow *et al.* [112]. This correction is given in Equation 5.15, where Nu_H is the corrected Nu, a and b are constants.

$$Nu_H = \frac{Nu}{1 - a b} \quad (5.15)$$

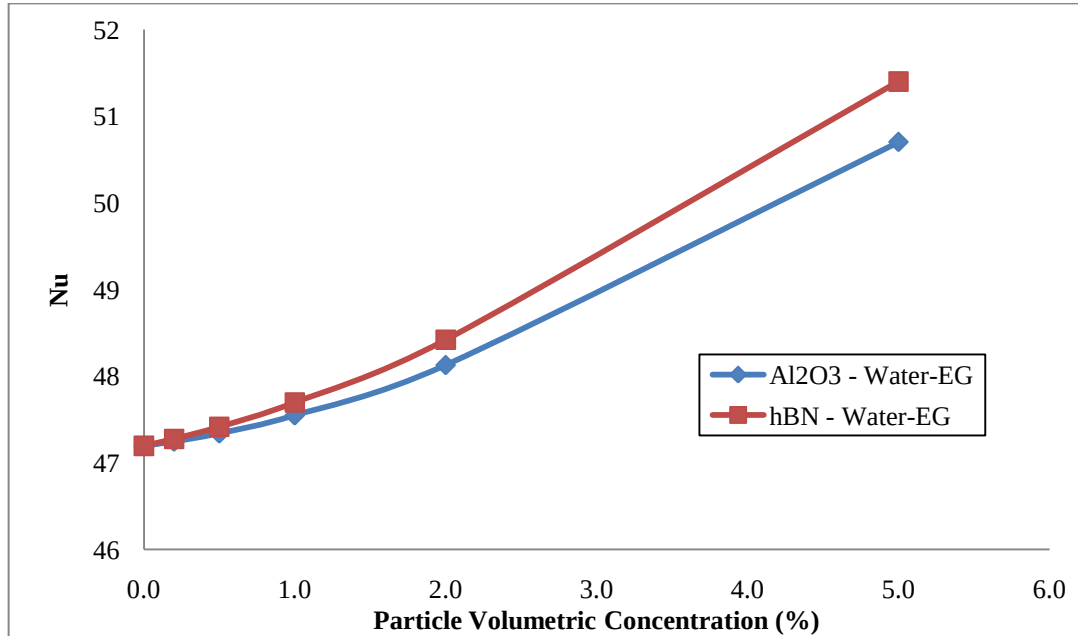


Figure 5.4. Theoretical Nu values for Al₂O₃ and hBN nanofluids.

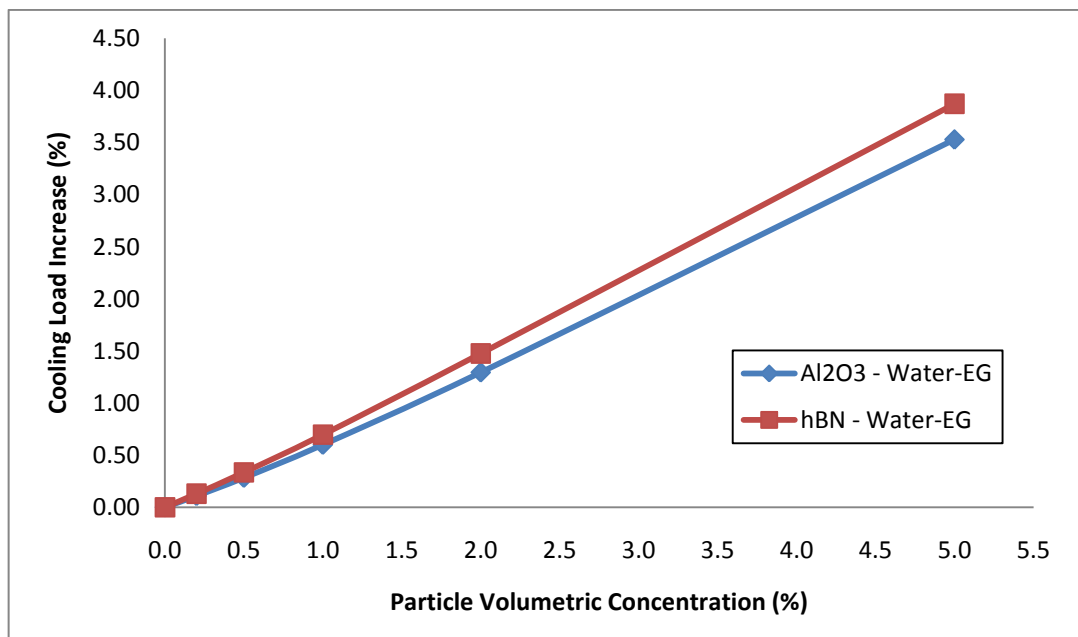


Figure 5.5. Cooling load increase by theoretical calculations.

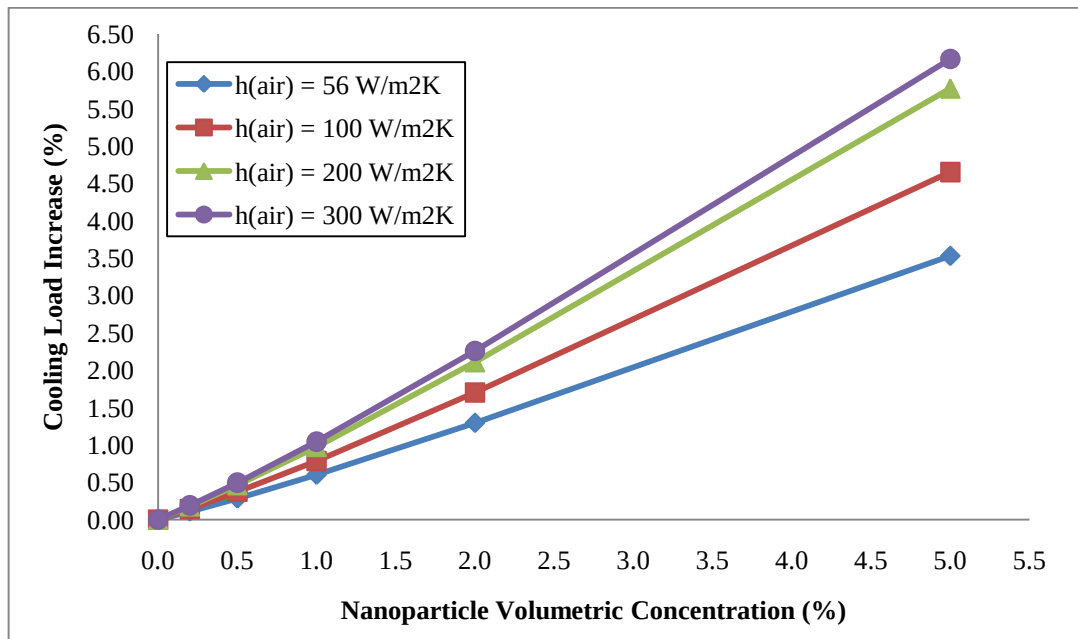


Figure 5.6. Cooling load increase of Al₂O₃ – Water-EG nanofluids.

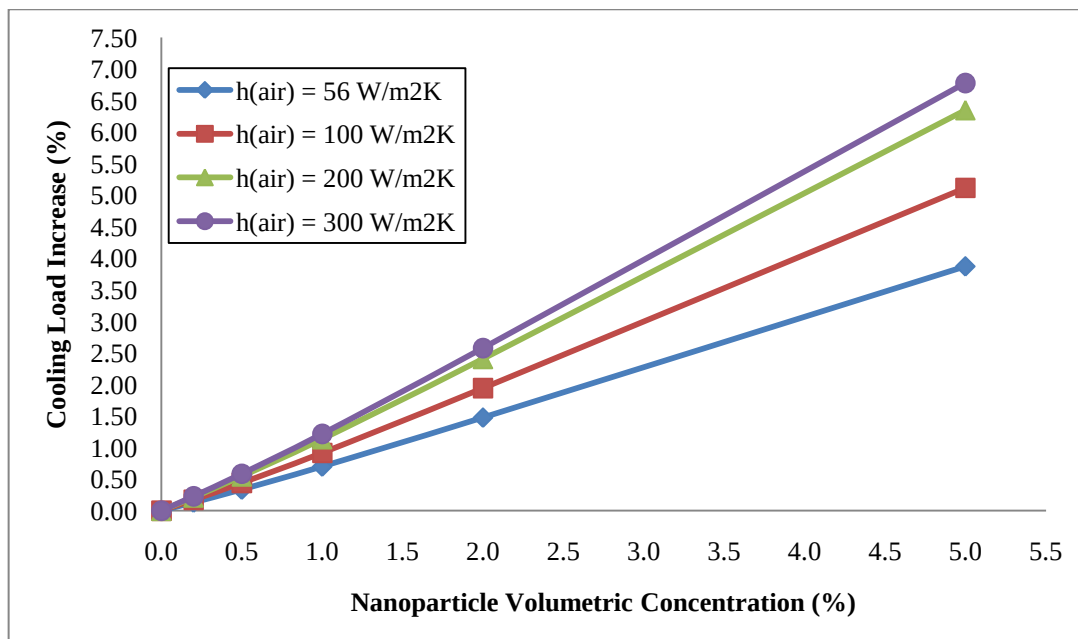


Figure 5.7. Cooling load increase of hBN – Water-EG nanofluids.

From Figure 5.6 and Figure 5.7 it can be concluded the amount of cooling load increases both with higher nanoparticle concentration and higher air heat transfer coefficient. However, it is also observed that the invery small difference between the results for 200 W/m²K and 300 W/m²K air transfer coefficient indicates that increasing air heat transfer coefficient will be ineffective after a certain value. The reason beyond this decrease of enhancement is the fact that fin efficiency decreases dramatically after a certain outside heat transfer coefficient.

Thermal performance enhancement with respect to air heat transfer coefficient for constant volumetric concentrations is presented in Figure 5.8 for Al₂O₃ and Figure 5.9 for hBN to clarify this observation. In each case of particle volumetric concentration, thermal performance enhancement increases with increasing air heat transfer coefficient. However, in each case in consideration the slope of the enhancement decreases as air heat transfer coefficient increases. This observation underlines the ineffectiveness of further air heat transfer coefficient increase. The same trend is also observed significantly in hBN nanofluids.

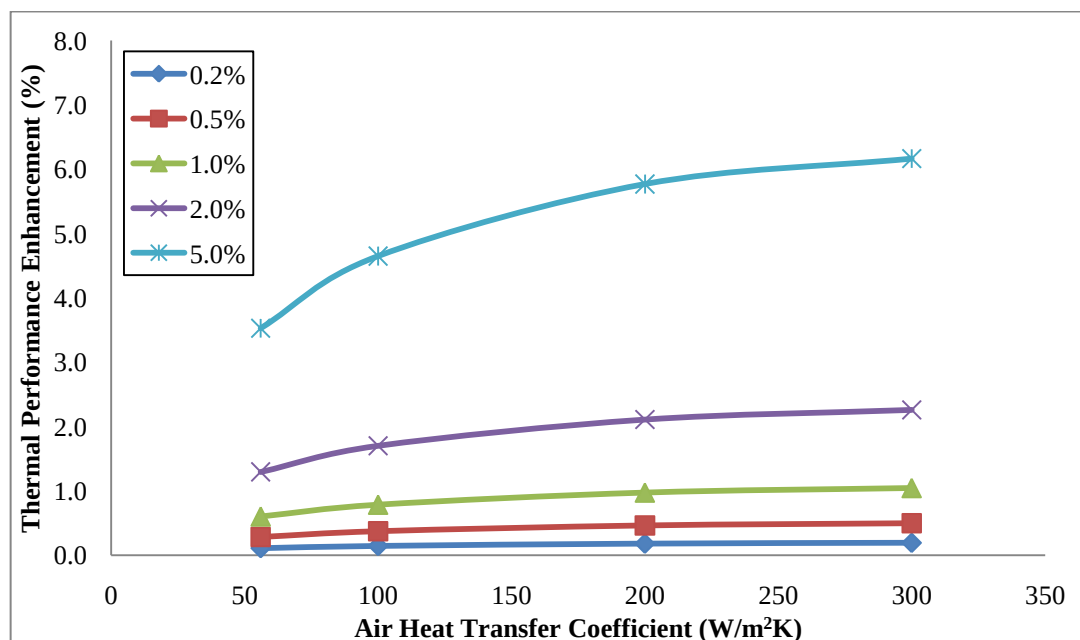


Figure 5.8. Thermal enhancement vs. air heat transfer coefficient in Al₂O₃.

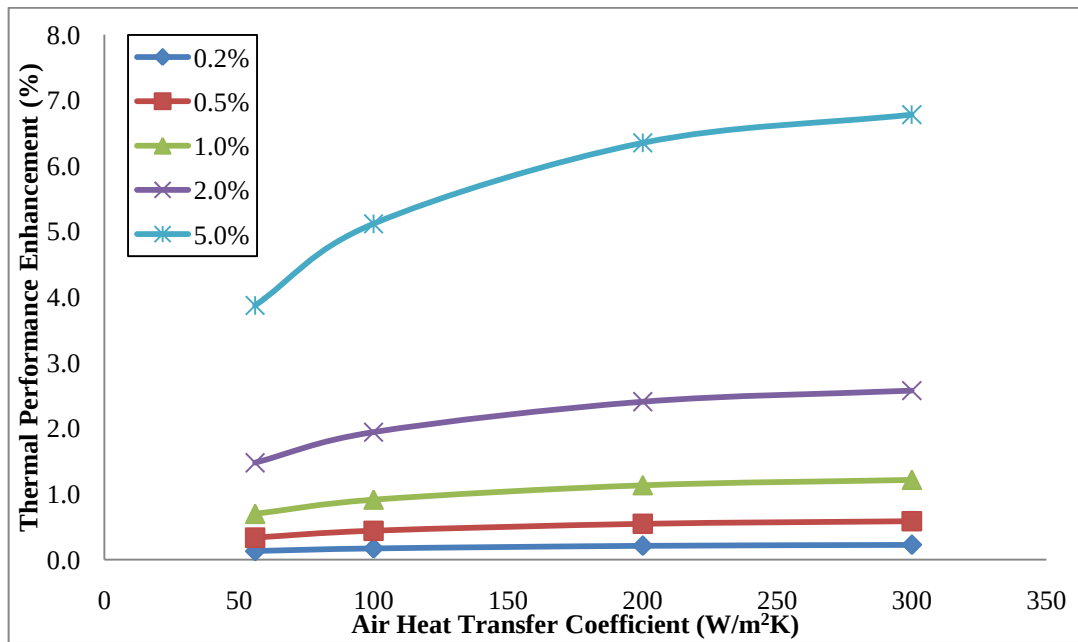


Figure 5.9. Thermal enhancement vs. air heat transfer coefficient in hBN.

Thermal performance enhancement with respect to air heat transfer coefficient graph for hBN nanofluids is presented Figure 5.9. Evaluation of the graph shows that, hBN containing nanofluids show also a similar trend. In conclusion, improving air heat transfer coefficient after an optimal point does not affect cooling performance of the system.

Further investigation on this topic leads to the comparison of air side and coolant side contributions in heat transfer. For instance, the fluid side resistance, which can be obtained from the second term in right hand side of Equation 5.14, is calculated as 0.008374 K/W for the base fluid. For air side heat transfer coefficient of 56.23, air side resistance (first term in right hand side of Equation 5.14) is 0.076781 K/W, an incredibly higher value with respect to liquid side resistance. However, for air side heat transfer coefficients of 100, 200 and 300 W/m²K, air side resistance is calculated as 0.04559, 0.023578 and 0.018523 K/W. It can be observed from these results that air side resistance drops dramatically with increasing air side heat transfer coefficient. Therefore, fluid side properties gain more importance. However, it can also be observed that the rate of this drop decreases as air heat transfer coefficient increases. The difference of resistances is significantly higher between 100 and 200 W/m²K with respect to the difference between

200 and 300 W/m²K. This type of behavior is observed for each volumetric concentration of nanofluids.

To evaluate the maximum thermal performance increase of the radiator and comparing the efficiency of the results for Al₂O₃ and hBN nanofluids, the ideal case of zero fluid resistance is introduced to the system, and the performance enhancement is estimated. In this case, the fluid does not affect the system as a resistance, and the only factor besides the flow geometry is the air side heat transfer coefficient. The results are calculated as 8.2% for 56.27 W/m²K and 16.7% for 300 W/m²K respectively. From Figure 5.8 and Figure 5.9, it can be concluded that 5% volumetric concentration is close to the limiting value at 300 W/m²K.

Due to the limited cooling load increase with respect to the addition of nanoparticles, the difference of Al₂O₃ and hBN containing nanofluids can be observed better when the cooling load improvement ratios of heat transfer enhancement with respect to each other is evaluated. Therefore, the ratio of additional cooling load for hBN to the base cooling load of Al₂O₃ is used for the same volumetric concentrations and boundary conditions (Equation 5.16).

$$\phi = \frac{Q_{hbn} - Q_b}{Q_{Al_2O_3} - Q_b} \quad (5.16)$$

In Equation 5.16 Q_b , Q_{hbn} and $Q_{Al_2O_3}$ are cooling loads of base fluid, hBN nanofluid and Al₂O₃ nanofluid respectively, and ϕ is the additional cooling load increase. The results are presented in Figure 5.10. The results in Figure 5.10 are unaffected from air heat transfer coefficient. It is observed that the additional cooling load due to the nanoparticle material change is very effective especially for low concentrations. For hBN, nearly 20% cooling load increase occurs in volumetric concentration of 0.2%. However, it drops down to 10% at 5% particle volumetric concentration. The importance of material decreases with increasing concentration. Finally, despite more significant effect of particle material in low particle volumetric concentrations, the overall heat transfer enhancement is very low.

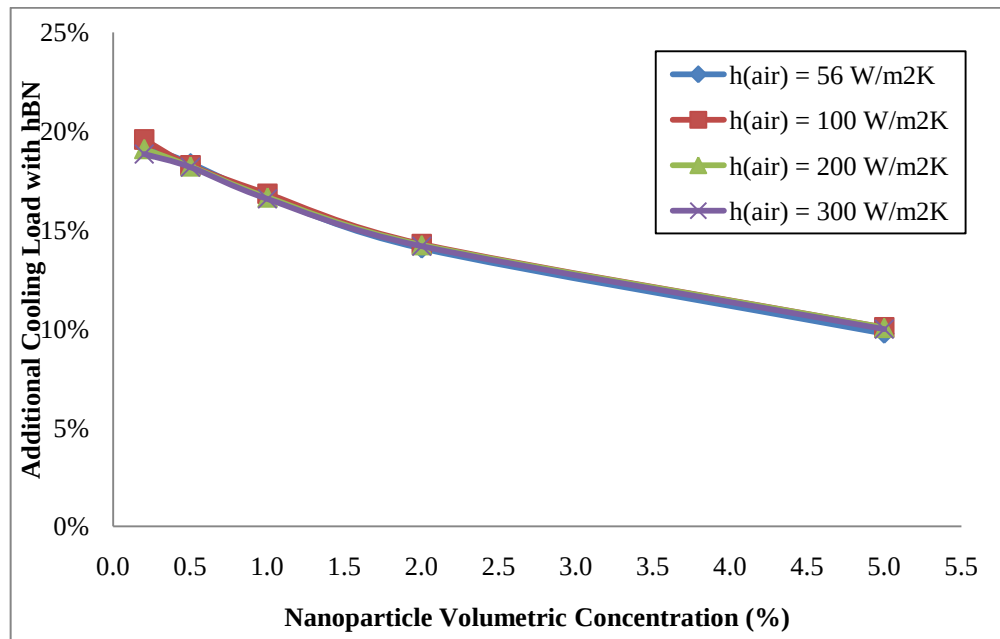


Figure 5.10. Additional cooling load increase for using hBN instead of Al_2O_3 .

Increasing radiator frontal area provides considerably higher enhancement. For frontal area of double size, it is observed that thermal enhancement is increased for both Al_2O_3 and hBN containing nanofluids. As the frontal area doubled by keeping the aspect ratio constant, the thermal performance enhancement Al_2O_3 of increased from 3.53% to 4.35% for 56.27 $\text{W/m}^2\text{K}$ air heat transfer coefficient and 5% volumetric concentration, whereas the enhancement for 300 $\text{W/m}^2\text{K}$, increased from 6.2% to 7.62% (Figure 5.11). Similar trend has been observed for hBN in Figure 5.12, where the enhancement increased from 3.9% to 4.79% at 56.27 $\text{W/m}^2\text{K}$ air heat transfer coefficient, and the enhancement increased from 6.8% to 8.38% at 300 $\text{W/m}^2\text{K}$. Results for other volumetric concentrations in both nanofluids and the effect of air heat transfer coefficient to the performance are also presented in Figure 5.11 and Figure 5.12. Similar to the original radiator size, results show that the cooling performance enhancement shows a linear increase with respect to particle nanoparticle concentration for each case. The slope of the enhancement line increases with increasing air heat transfer coefficient.

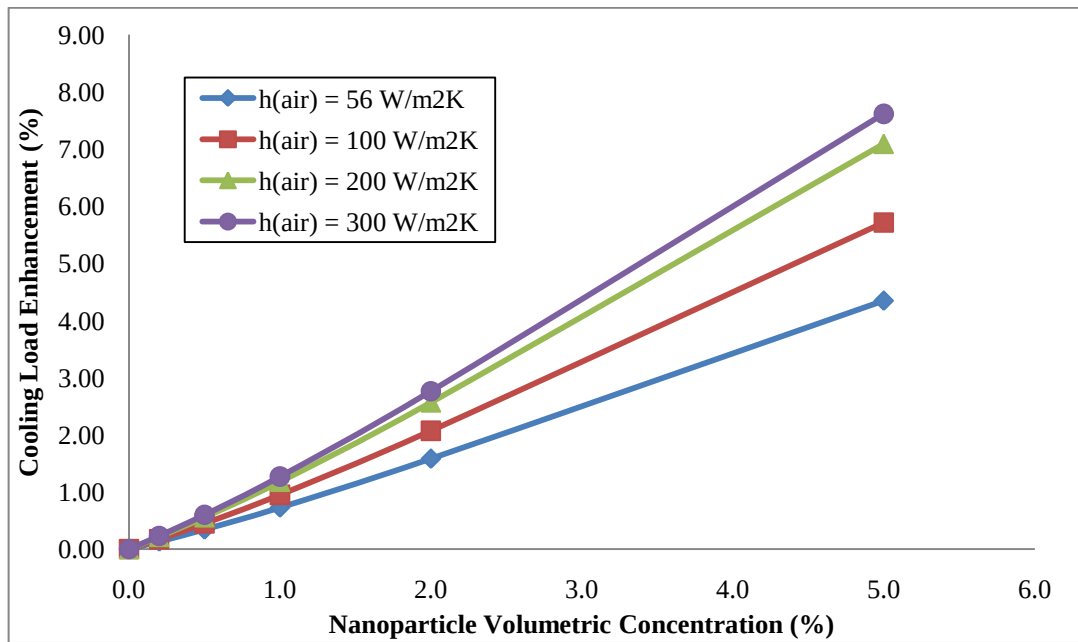


Figure 5.11. Thermal performance enhancement for Al_2O_3 in a larger radiator.

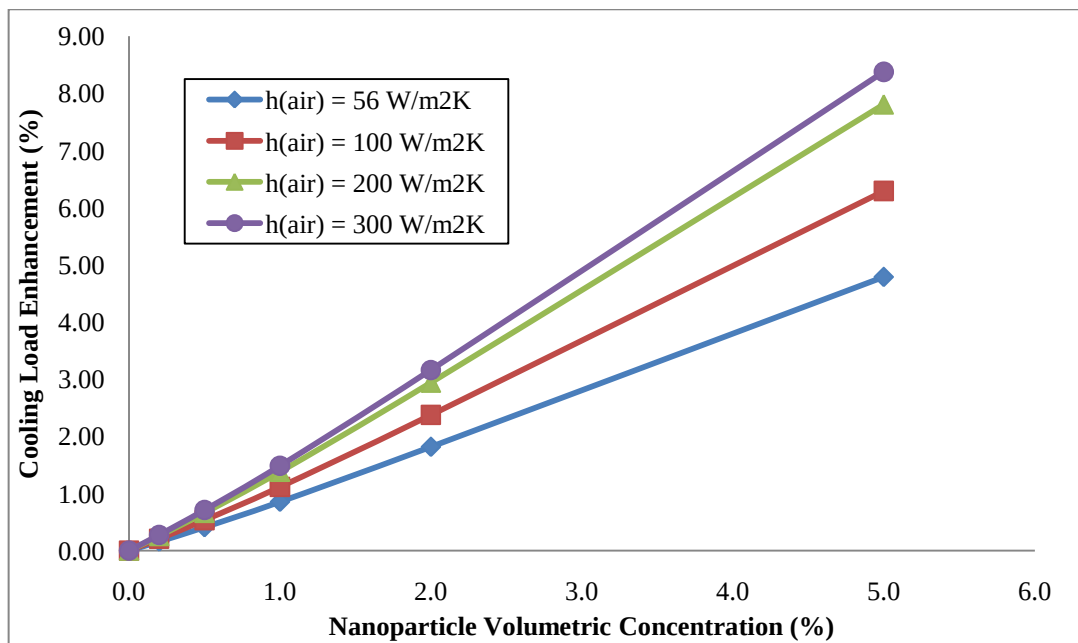


Figure 5.12. Thermal performance enhancement for hBN in a larger radiator.

Figure 5.13 shows the thermal performance enhancement with respect to area change. The radiators in consideration have the same aspect ratio as the specified large radiator specified in previous calculations; however the size of the radiator is increased by constant values. As specified before, thermal conductivities of nanofluids in this study are estimated by using Maxwell correlation so far. However, Leong's results show an anomalous deviation from Maxwell's correlation. A similar derivation is also a possibility for hBN. Therefore, the possibility of higher thermal conductivity enhancements has to be examined as well. In order to do that evaluation, an enhancement factor is used on Maxwell's correlation to cover possible higher effective thermal conductivities. Thermal conductivity enhancement of the nanofluid is multiplied by this enhancement factor, and the result is used to calculate thermal performance enhancement. The factor is taken as various values above 1. Figure 5.14 contains the results for this evaluation, evaluating the factor up to 16. As it can be seen from the figure, Thermal enhancement increases for each volumetric concentration of hBN, following the same trend each time.

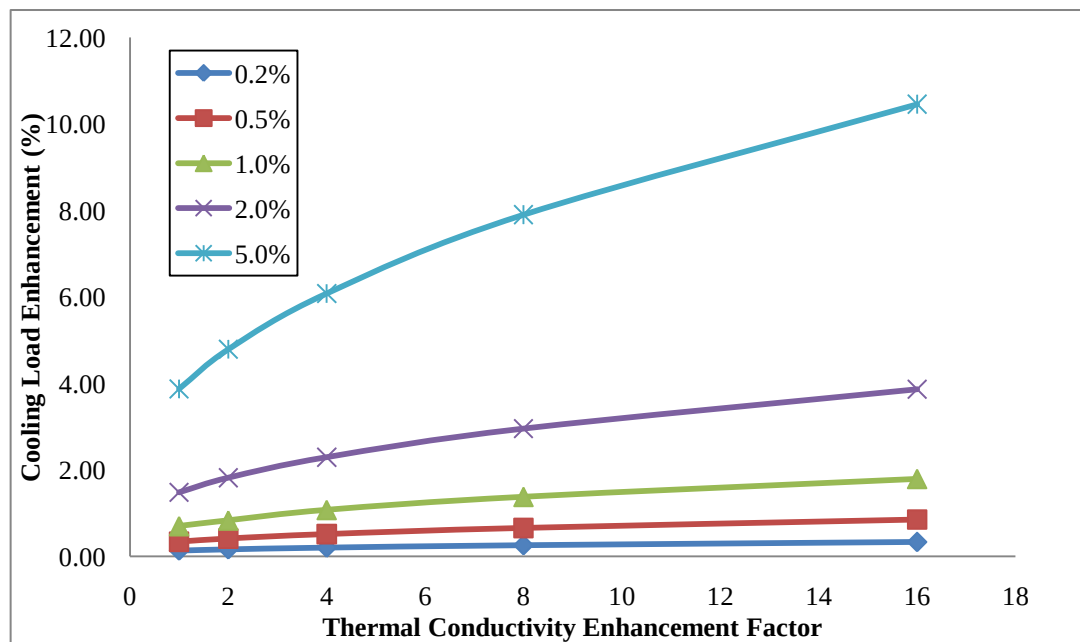


Figure 5.13. Thermal performance enhancement change due to frontal area.

5.2.2. Numerical Results

Both nanofluids have been analyzed numerically in order to determine their thermal behavior and compare with theoretical results in a full range of the volumetric concentration and boundary condition matrix to compare the results.

It is observed that numerically calculated Nusselt number of the nanofluids is in good agreement with the results from the corrected Dittus-Boelter correlation (Figure 5.14). This behavior corresponds with previous results from Chapter 3. Similarly, cooling load enhancement is in good agreement with previous section with a slight deviation at high volumetric concentrations, which is in acceptable limits (Figure 5.15).

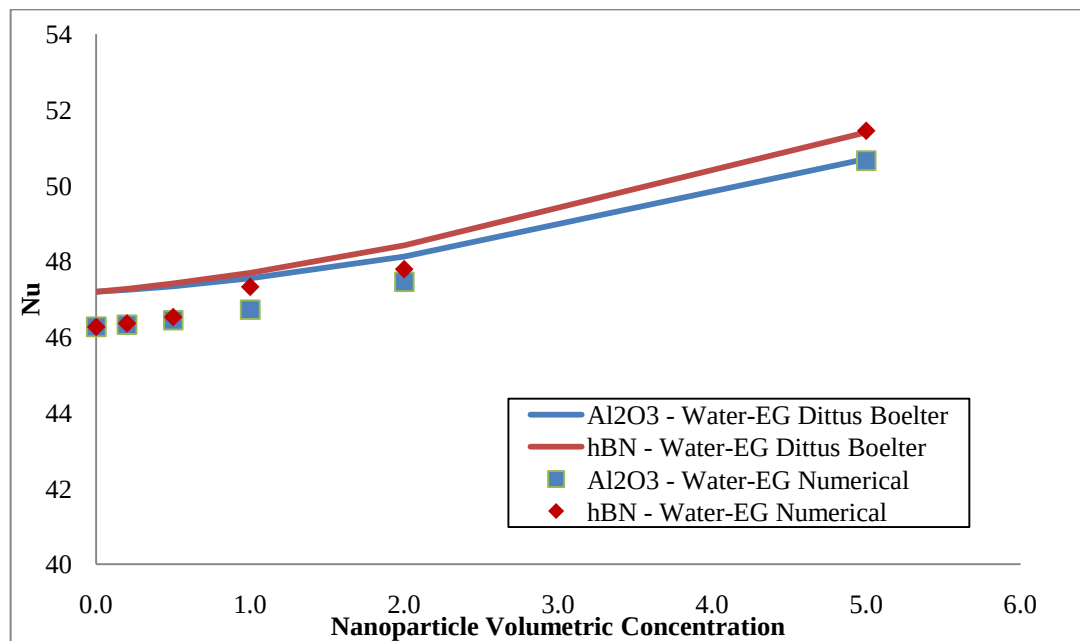


Figure 5.14. Nusselt number comparison of theoretical and numerical results.

For a single tube and $56.27 \text{ W/m}^2\text{K}$ air heat transfer coefficient as boundary condition, total heat transfer is calculated theoretically as 1414.2 W for pure water, increases to 1455.3 W for 5% Al_2O_3 and 1459.2 W for 5% hBN volumetric concentrations. The analysis for $300 \text{ W/m}^2\text{K}$ air side heat transfer coefficient on the other hand gives a

1441.4 W pure water total heat transfer, and 1485.9 W and 1490.1 W for 5% volumetric concentrations of Al_2O_3 and hBN respectively.

Total cooling load increase of both nanofluids by air boundary condition of $56.27 \text{ W/m}^2\text{K}$ is given in Figure 5.16. Similar to the theoretical results, total cooling load enhancement increases with increasing air side heat transfer coefficient. The difference is small at small heat transfer rate. To illustrate, for Al_2O_3 containing nanofluids at $56.27 \text{ W/m}^2\text{K}$ air heat transfer coefficient, numerical result for heat transfer enhancement rate is 1.2% at 2% particle volumetric concentration, whereas it was 1.3% according to the theoretical calculations. At 5% particle volumetric concentration the difference shows an enhancement of 3.1% numerically, whereas it was 3.5% whereas according to the theoretical calculations. Increasing the air side heat transfer coefficient to $300 \text{ W/m}^2\text{K}$ allows a more effective contribution of nanoparticles, increasing the total heat transfer improvement, showing numerically 2.7% cooling load increase for 2% volumetric concentration, whereas 2.1% theoretically. Similarly, a more significant improvement is observed at 5% volumetric concentration, increasing total cooling load enhancement from 6.1% to 8.1%.

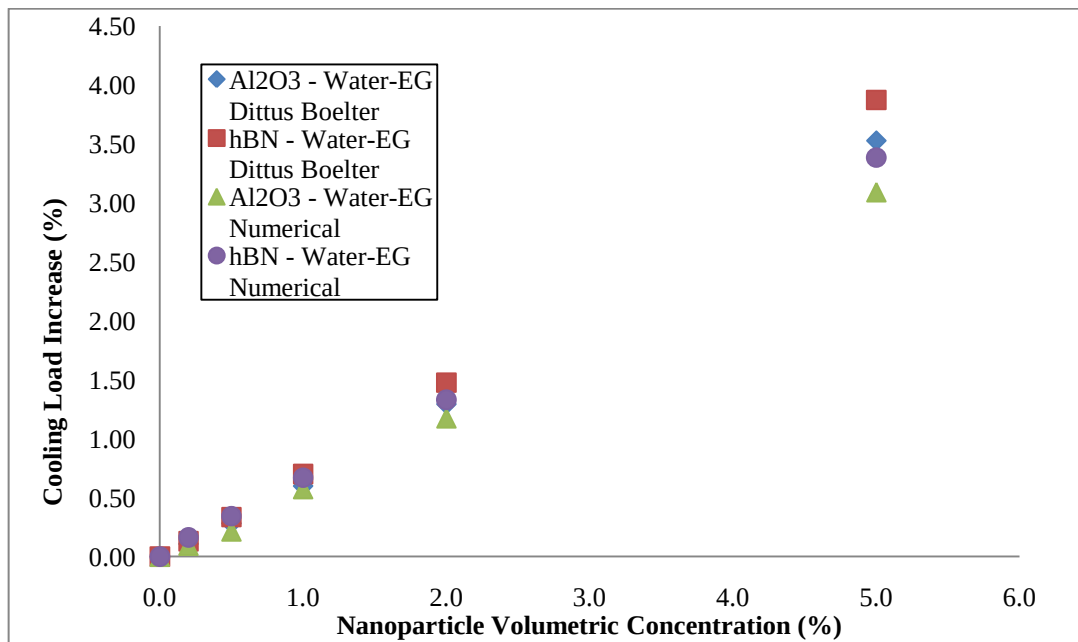


Figure 5.15. Heat transfer increase for theoretical and numerical calculations.

Hexagonal boron nitride shows a better improvement rate in each air side boundary condition. Inspecting the results of $56.27 \text{ W/m}^2\text{K}$ air side heat transfer coefficient, it can be observed that the heat transfer enhancement is 1.3%, slightly lower than theoretical calculations of 1.5%, 2% volumetric concentration and, found as 3.4% for 5% particle volumetric concentration. However, the enhancement is higher than theoretical calculations in higher air side heat transfer coefficients. To illustrate, the numerical calculation of thermal enhancement of 2% hBN particles gives the result of 3.5% for $300 \text{ W/m}^2\text{K}$, whereas theoretically it was 2.6%.

Numerical results indicate that hBN is superior to Al_2O_3 in every set of simulations in terms of heat transfer enhancement (Figure 5.16). However, significance of particle material properties as well as the amount of additional heat transfer due to the use of hBN changes with respect to several parameters such as boundary conditions of system and particle volumetric concentration..

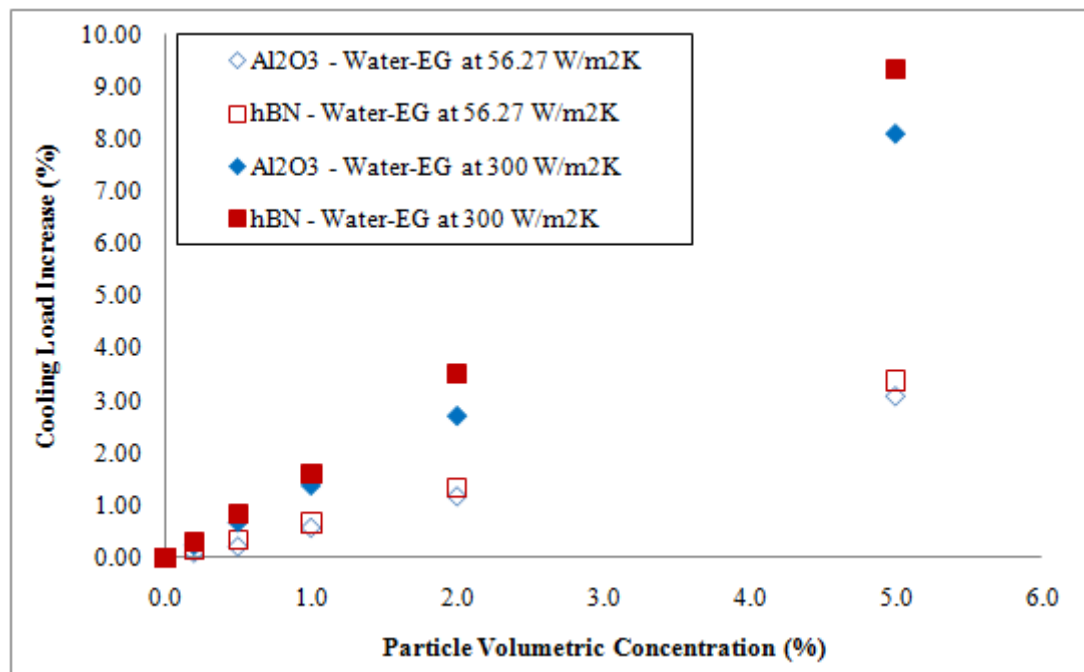


Figure 5.16. Cooling load increase with respect to air heat transfer coefficient.

The general behavior pattern of hBN containing nanofluids with various volumetric concentrations and boundary conditions is shown in Figure 5.16. To illustrate, by numerical results, the choice of hBN nanoparticles causes an additional heat transfer enhancement of 28.9% with respect to heat transfer enhancement of Al_2O_3 at a boundary condition of $300 \text{ W/m}^2\text{K}$ air heat transfer coefficient and 0.2% particle fraction, whereas it drops to 14.9% at 5% particle fraction on the same boundary condition. This behavior was also predicted in theoretical analysis and shown in Figure 5.8

In each case studied numerically, it has been observed that the results are in exceptionally good agreement with correlation approximations. Therefore the results in Section 5.2.1 are accepted as the final results for further analyses.

5.2.3. Further Evaluation

In Section 5.2.1 and Section 5.2.2, theoretical Maxwell correlation has been used to calculate the thermal conductivity of the nanofluids. Moreover, Reynolds number of the nanofluids is taken constant throughout the analysis, neglecting the effect on the pumping power. Therefore, further evaluation is necessary to simulate experimental cases. In this Section, two further cases will be investigated. In the first case, instead of using Maxwell correlations experimental data set for thermal conductivity enhancement will be used as input, and the difference will be inspected. In the second case, instead of constant Reynolds number, the effect of the change in Reynolds number is also included, and the resulting performance is investigated.

It has been observed by Li *et al.* [103], that the experimentally measured thermal conductivity of hBN containing nanofluids is significantly higher than Maxwell correlation results. Their results have been applied to the system in order to increase the accuracy of the analysis. Nusselt number change of the system, calculated by using Dittus-Boelter correlation and heat exchanger formulations, is presented in Figure 5.17. As it can be observed, the Nusselt number is lower for the results using experimental thermal conductivity data. The difference is based on the inverse proportionality between Nusselt number and thermal conductivity by definition.

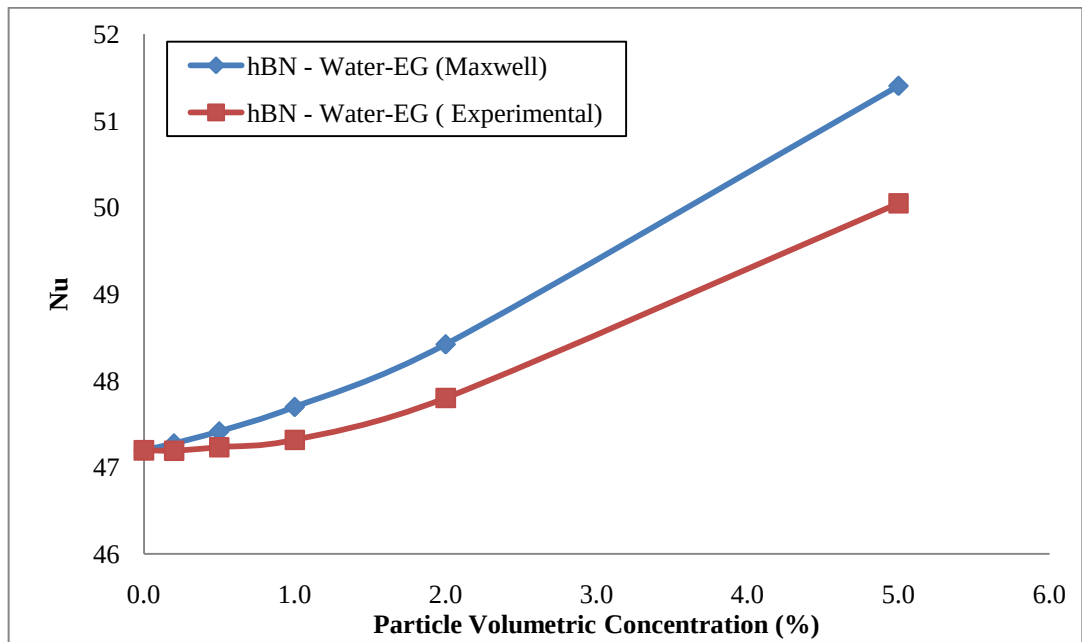


Figure 5.17. Nusselt number change with respect to particle volumetric concentration.

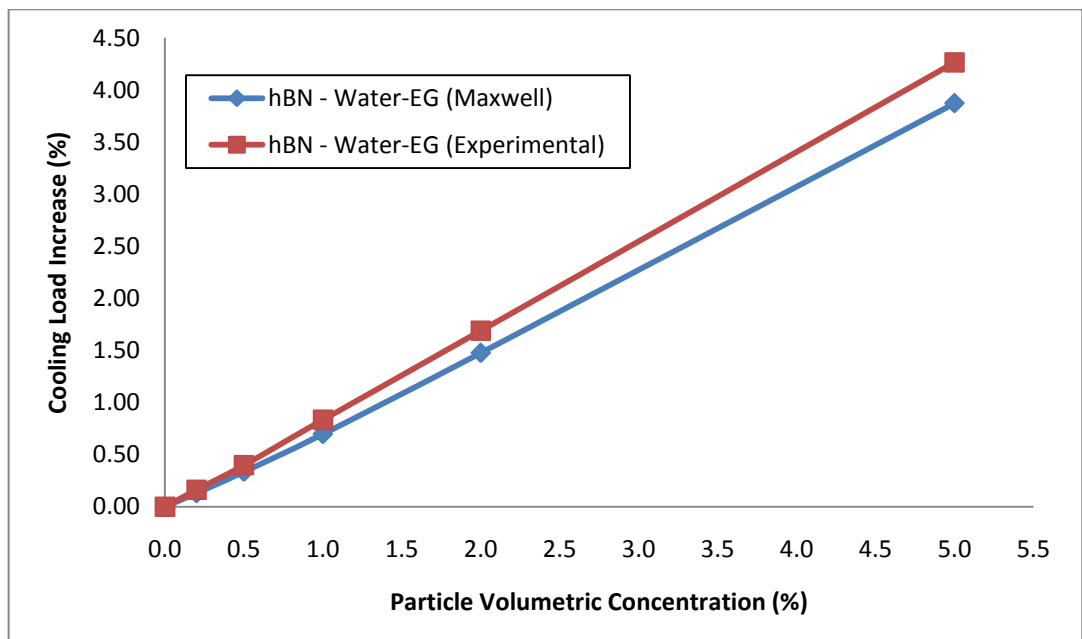


Figure 5.18. Thermal performance enhancement comparison.

On the other side, it is observed that thermal performance enhancement is slightly higher for the case with experimental thermal conductivity data set. Thermal performance enhancement increases up to 4.3% for experimental data set with 5% particle volumetric concentration. The reason behind this behavior is the proportionality between thermal conductivity of the fluid and thermal performance. The comparison of both thermal conductivity data sets is presented in Figure 5.18.

Previous results in Section 5.2.2 confirmed a good agreement between theoretical calculations and numerical work. A similar trend is also observed for the results for experimental thermal conductivity data set. As it can be seen in Figure 5.19, thermal performance enhancement for the experimental thermal conductivity data set shows similar results for correlations and numerical approximations.

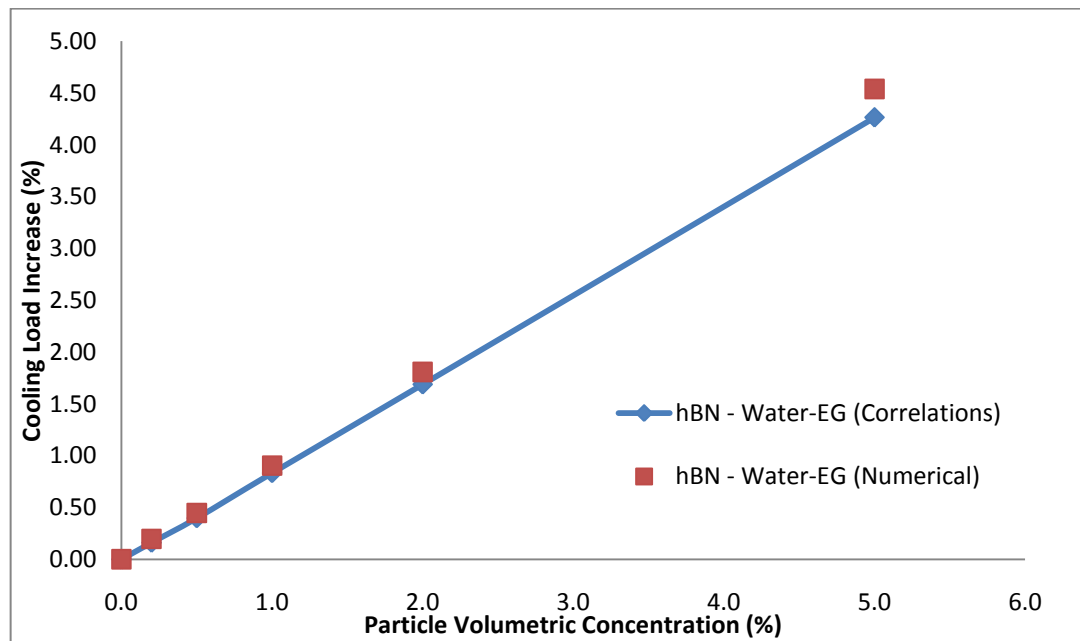


Figure 5.19. Thermal enhancement comparison for correlations and analyses.

Using correlations, the evaluation for various air side heat transfer coefficients are given in Figure 5.20. The trend is very similar to the results in Section 5.2.2, the maximum thermal performance enhancement having been obtained at 5% particle volumetric concentration and air side heat transfer coefficient of $300 \text{ W/m}^2\text{K}$ as 7.56%.

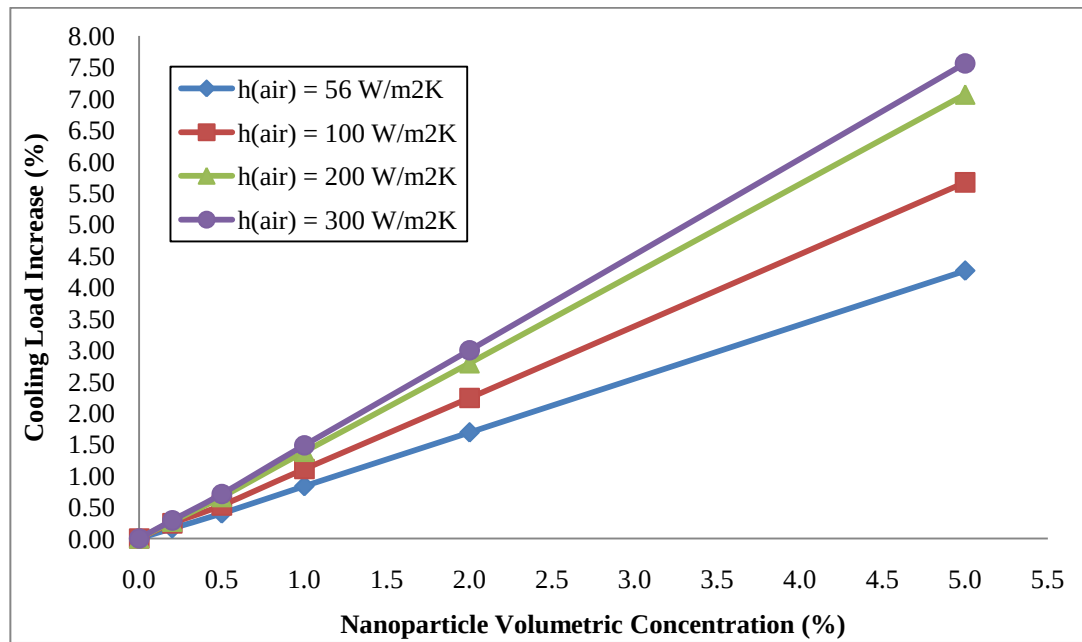


Figure 5.20. Thermal performance enhancement for various boundary conditions.

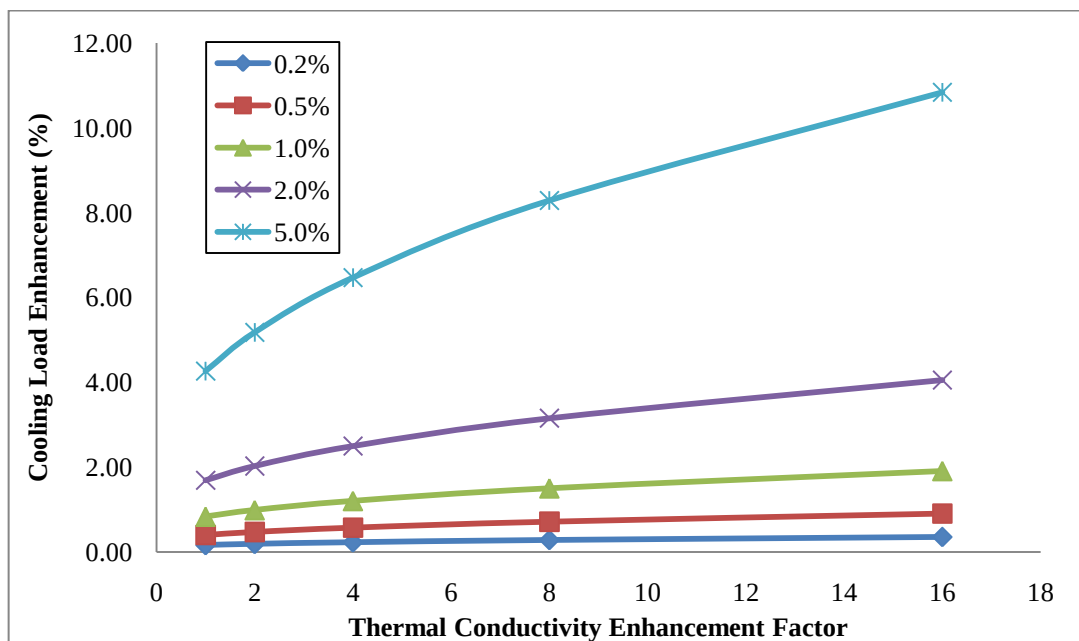


Figure 5.21. The effect of radiator size.

Radiator size increase also shows a similar effect on thermal performance enhancement. The enhancement increases with increasing radiator size. The improvement is stronger at smaller ratio improvements; however, after a certain point it shows a linear increase. The effect of radiator size change is presented in Figure 5.21.

As a final evaluation, the performance change for the same pumping system will be investigated. For this purpose; the rate of work done (Equation 5.17) is kept constant and the change in Reynolds number will be included in the calculations. Purely effect of nanofluid addition will be investigated.

$$\dot{W} = \Delta p \dot{V} \quad (5.17)$$

Pressure difference Δp and volumetric flow rate $\dot{V}$ are calculated from the following formulations in Equation 5.18 and Equation 5.19. Relating friction factor to Reynolds number by using Blasius correlation in Equation 5.20 and removing the constant values, Equation 5.21 is obtained. Thermal performance enhancement ratios, calculated using variable Reynolds numbers, are given in Figure 5.22 for Maxwell correlation and Figure 5.23 for experimental data set. It is observed that for the same pump work, addition of boron nitride nanoparticles does not increase the cooling load. On the contrary, a slight negative effect is observed. This rapid decrease is the result of dramatic Reynolds number decrease. The base Reynolds number of 6500 for pure water decreases to 3864.2 for 5% particle volumetric concentration.

$$\Delta p = f \frac{L \rho v^2}{2 D} \quad (5.18)$$

$$\dot{V} = v A_c \quad (5.19)$$

$$f = \frac{0.3164}{Re^{0.25}} \quad (5.20)$$

$$\frac{Re^{2.75} \mu^3}{\rho^2} = \text{constant} \quad (5.21)$$

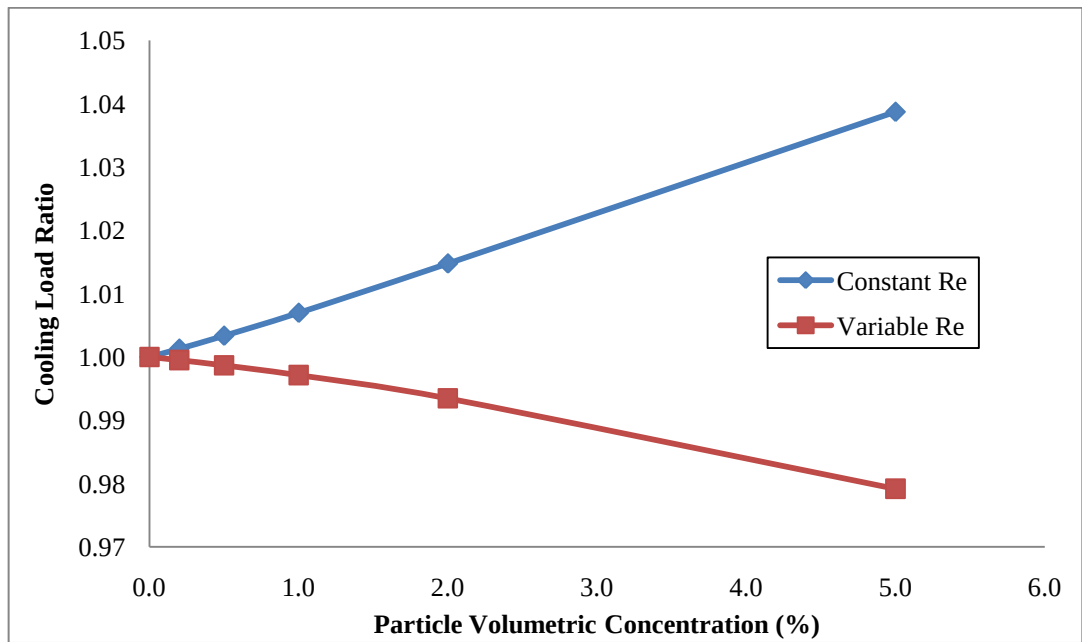


Figure 5.22. Thermal performance ratio for Maxwell correlation results.

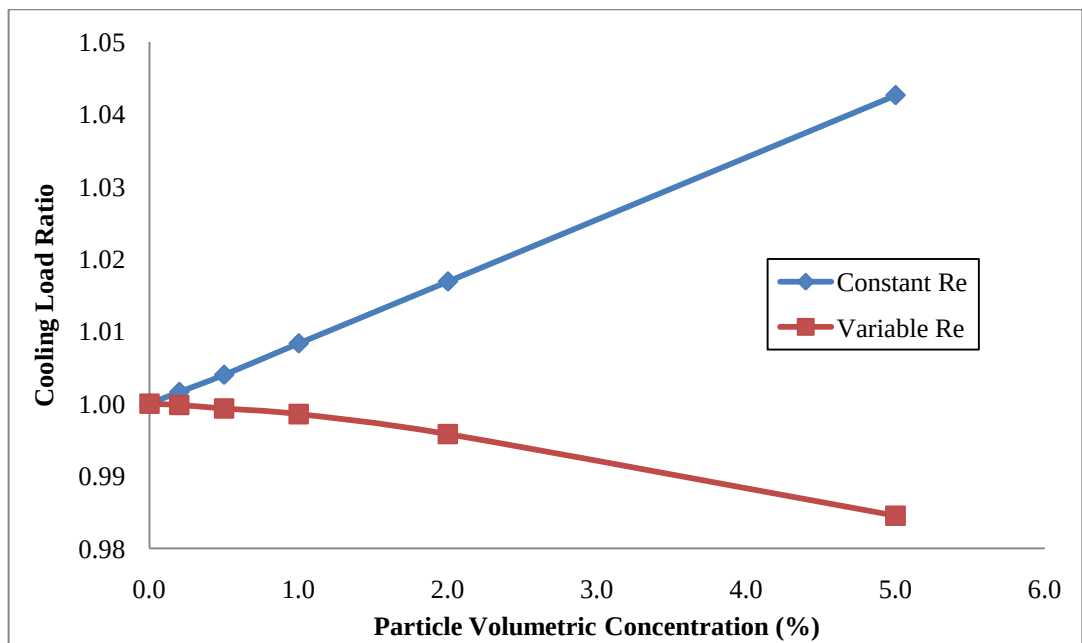


Figure 5.23. Thermal performance ratio for experimental data set.

Both figures show the condition for the boundary condition of air side heat transfer coefficient same work is done for $56.27 \text{ W/m}^2\text{K}$. However, it is observed that increasing air side heat transfer coefficient has negligible effect on the results. Similarly, changing the radiator size does not have an effect on the results of Figure 5.22 and Figure 5.23. Therefore, it can be concluded that for the same pump using hBN nanofluids does not give any advantage in terms of cooling load enhancement.

6. CONCLUSION

6.1. Discussion and Concluding Remarks

Throughout the study, heat transfer behavior of hBN containing nanofluids has been investigated both by numerical methods and correlations, and the results are compared to the results obtained from various other nanofluids in each case. Throughout the numerical analyses, single phase modeling has been used.

After the verification of the numerical model in Chapter 3, heat transfer behavior analysis of hBN – Water nanofluids with different particle volumetric concentrations has been analyzed for turbulent flow condition with two different Reynolds number sets (6000 and 10000) in Chapter 4. Both Reynolds number analyses have shown similar behavior in heat transfer application. A significant increase in Nusselt number and a higher increase in heat transfer coefficient with increasing nanoparticle volumetric concentration is observed for both flow rates. This behavior is in good agreement with various results for other nanofluids in literature. It is also shown that hBN containing nanofluids show significantly better thermal properties with respect to TiO_2 , Al_2O_3 and diamond containing nanofluids, which are also evaluated throughout the chapter for comparison.

Chapter 5 is concentrated on an internal combustion engine radiator analysis for alumina hexagonal boron nitride containing nanofluids. A sample radiator geometry with given specifications is focused on, and various analyses on this radiator have been carried out. It has been observed that the amount of additional cooling load with respect to nanoparticle fraction increases with higher air side heat transfer coefficient, which leads to the idea of air channel optimization and additional precautions to increase air inlet velocity for higher heat transfer improvement. Similarly, the frontal area of the radiator is modified to evaluate the effect of the radiator size to the analysis. The initial analyses have been carried out with nanofluid thermal conductivity results calculated by Maxwell correlation, whereas afterwards an experimental thermal conductivity data set from literature is also used to investigate the difference. After the initial analyses with constant Reynolds number of 6500, the case with constant pumping power is investigated.

The analyses clearly indicate that numerical analysis and Dittus-Boelter correlations give similar results. Another conclusion is that the heat transfer enhancement by hBN nanofluids is significantly higher than the heat transfer enhancement of other nanoparticles. Chapter 4 provides a comparison of hBN with various nanoparticles in cylindrical tube analysis. Similarly, according to the results of Chapter 5, it is observed that hBN gives considerably better results for cooling load improvement in each set of numerical analyses, having up to 13.4% higher additional cooling load for particle volumetric concentration of 0.2% with respect to the additional cooling load of Al_2O_3 nanofluid of same concentration for the effective air heat transfer coefficient of $56.27 \text{ W/m}^2\text{K}$. Therefore, it can be concluded from Chapter 5, that hexagonal boron nitride is far more favorable as a nanoparticle material with respect to Al_2O_3 . Therefore hBN is accepted as a very good nanoparticle material. However Chapter 5 showed that the thermal performance enhancement by the application of nanoparticles is very small for practical applications even for hBN. Moreover investigating the effect of constant pumping power instead of constant Reynolds number has shown slight decrease in cooling performance, which is a remarkable behavior. The validity of this conclusion has to be confirmed experimentally.

Leong's work indicates that an anomalously larger additional cooling load can be achieved by using experimental results for thermal properties of nanofluids. However the results of this study vary from Leong's results in terms of heat transfer enhancement rate. The reasons and detailed explanations can be found in Appendix B. It should be noted that the whole simulation is based on theoretical knowledge and common estimation methods in literature, since hBN containing nanofluids are still not fully studied experimentally for their thermal performance.

One interesting conclusion is that the importance of nanoparticle material and nanoparticle thermo-physical properties reduces with both higher particle fraction and higher effective air heat transfer coefficient in constant Reynolds number analyses. In other words, although the total cooling load improvement is significantly higher for higher particle volumetric concentrations and air side effective heat transfer coefficient, the effect of nanoparticle material superiority is mostly observed in lower concentration.

As a last comment, it is obligatory that the results have to be verified experimentally, and the validity of correlations to calculate thermal and physical properties of the hBN nanofluid has to be examined.

6.2. Suggestions for Future Work

Throughout the numerical analyses single phase modeling method is used to approximate thermal performance enhancement. A two phase modeling may be used in order to investigate the effect of the factors which are neglected or simplified for single phase analysis.

Leong's study has proven that experimental and theoretical results may vary significantly for general performance analysis. Therefore, it is necessary to conduct effort for experimental study to verify or revise the input data for hBN – Water-EG nanofluids, which are calculated by correlations. The effect of hexagonal boron nitride nanoparticles is still a mystery in literature. Especially its thermo-physical behavior due to directional thermal conductivity has to be evaluated.

The performance evaluation of hBN nanofluids on the same pumping system has to be investigated experimentally, and the validity of the variable Reynolds number case should be evaluated.

APPENDIX A: TURBULENCE MODELS

Standard k- ω Model

Standard k- ω model uses the following transport equations to introduce kinetic turbulence energy K and specific dissipation rate ω .

$$\frac{\partial}{\partial t}(\rho K) + \frac{\partial}{\partial x_i}(\rho K u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_K \frac{\partial K}{\partial x_j} \right) + G_K - Y_K + S_K \quad (\text{A.1})$$

$$\frac{\partial}{\partial t}(\rho \omega) + \frac{\partial}{\partial x_i}(\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_\omega \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + S_\omega \quad (\text{A.2})$$

In above equations G_k is turbulence kinetic energy generation due to mean velocity gradients, G_ω is ω generation, and Γ_K and Γ_ω represent the effective thermal diffusivity of K and ω respectively. Y_k and Y_ω are defined as dissipation of K and ω due to turbulence. S_k and S_ω are the contribution of user-defined source items. Γ values are calculated by following equations:

$$\Gamma_K = \mu + \frac{\mu_t}{\sigma_K} \quad (\text{A.3})$$

$$\Gamma_\omega = \mu + \frac{\mu_t}{\sigma_\omega} \quad (\text{A.4})$$

where μ_t is found as

$$\mu_t = \frac{\rho K}{\omega} \quad (\text{A.5})$$

δ_K and δ_ω are the turbulent Prandtl numbers for k and ω . Other terms in Equations A.6 and A.7 are given as:

$$G_k = -\rho \bar{u}_j \bar{u}_j \frac{\partial u_j}{\partial x_i} \quad (A.6)$$

$$G_\omega = \alpha \frac{\omega}{K} G_k \quad (A.7)$$

$$\alpha = \alpha_\infty \left(\frac{a_0 + Re_t / Re_\omega}{1 + Re_t / Re_\omega} \right) \quad (A.8)$$

Dissipation for K is calculated as following:

$$Y_K = \rho \beta_\infty f_\beta K \omega \quad (A.9)$$

$$f_\beta = \begin{cases} 1 & X_K \leq 0 \\ \frac{1+680X_K^2}{1+400X_K^2} & X_K > 0 \end{cases} \quad (A.10)$$

where X_K can be found as

$$X_K \equiv \frac{1}{\omega^3} \frac{\partial K}{\partial x_j} \frac{\partial \omega}{\partial x_j} \quad (A.11)$$

Similarly dissipation for ω can be obtained:

$$Y_\omega = \rho \beta f_\beta \omega^2 \quad (A.12)$$

$$f_\beta = \frac{1+70X_\omega}{1+80X_\omega} \quad (A.13)$$

$$X_\omega = \left| \frac{\Omega_{ij} \Omega_{jl} S_{k,i}}{(\beta_\infty \omega)^3} \right| \quad (A.14)$$

$$S_{ij} = \frac{1}{2} \left(\frac{\partial u_j}{\partial x_i} + \frac{\partial u_i}{\partial x_j} \right) \quad (\text{A.15})$$

Model constants are given below in Table A.1.

Table A.1. Constants for standard k- ω model.

Constant	Value
α_∞	0.52
α_0	1.9
β_∞	0.09
β_t	0.072
R_β	8
R_{kt}	6
R_ω	2.95
ζ^*	1.5
M_{t0}	0.25
σ_{kt}	2
σ_ω	2

SST k- ω model

Similarly SST k- ω model uses two transport functions.

$$\frac{\partial}{\partial t} (\rho K) + \frac{\partial}{\partial x_i} (\rho K u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_K \frac{\partial K}{\partial x_j} \right) + \check{G}_K - Y_K + S_K \quad (\text{A.16})$$

$$\frac{\partial}{\partial t} (\rho \omega) + \frac{\partial}{\partial x_i} (\rho \omega u_i) = \frac{\partial}{\partial x_j} \left(\Gamma_K \frac{\partial \omega}{\partial x_j} \right) + G_\omega - Y_\omega + D_\omega + S_\omega \quad (\text{A.17})$$

D_ω is the cross-diffusion term. Γ_K and Γ_ω values are obtained similar to standard k - ω model via equations 19a and 19b. The turbulent viscosity μ_t is, however, obtained differently, by using Equation A.18.

$$\mu_t = \frac{\rho K}{\omega} \frac{1}{\max \left[1, \frac{SF_2}{\alpha_1 \omega} \right]} \quad (\text{A.18})$$

S is the strain rate magnitude, and turbulent Prandtl numbers are given as:

$$\sigma_K = \frac{1}{F_1/\sigma_{K,1} + (1-F_1)/\sigma_{K,2}} \quad (\text{A.19})$$

$$\sigma_\omega = \frac{1}{F_1/\sigma_{\omega,1} + (1-F_1)/\sigma_{\omega,2}} \quad (\text{A.20})$$

where F_1 and F_2 are functions of φ with

$$F_1 = \tanh(\varphi_1^4) \quad (\text{A.21})$$

$$\varphi_1 = \min \left[\max \left(\frac{\sqrt{K}}{0.09\omega y}, \frac{500\mu}{\rho y^2 \omega} \right), \frac{4\rho K}{\sigma_{\omega,2} D_\omega^+ y^2} \right] \quad (\text{A. 22})$$

$$D_\omega^+ = \max \left[2\rho \frac{1}{\sigma_{\omega,2}} \frac{1}{\omega} \frac{\partial K}{\partial x_j} \frac{\partial \omega}{\partial x_j}, 10^{-10} \right] \quad (\text{A.23})$$

$$F_2 = \tanh(\varphi_2^2) \quad (\text{A.24})$$

$$\varphi_2 = \max \left[2 \frac{\sqrt{K}}{0.09\omega y}, \frac{500\mu}{\rho y^2 \omega} \right] \quad (\text{A.25})$$

In the equations above, y is the distance to the next surface, and D_{ω}^+ is the positive portion of the cross diffusion term.

The term $\check{G}_K$ represents turbulence kinetic energy production and calculated by the following definition:

$$\check{G}_K = \min(G_K, 10\rho\beta K\omega) \quad (A.26)$$

G_{ω} is defined as:

$$G_{\omega} = \frac{\alpha}{v_T} \check{G}_K \quad (A.27)$$

$$\alpha = F_1\alpha_{\infty,1} + (1-F_1)\alpha_{\infty,2} \quad (A.28)$$

Dissipations are obtained by following formulations:

$$Y_K = \rho \beta_{\infty} K \omega \quad (A.29)$$

$$Y_{\omega} = \rho \beta \omega^2 \quad (A.30)$$

where

$$\beta = F_1\beta_1 + (1-F_1)\beta_2 \quad (A.31)$$

Cross diffusion modification factor, introduced to blend k- ϵ and k- ω models is calculated as following:

$$D_{\omega} = 2(1-F_1)\rho\sigma_{\omega,2}\frac{1}{\omega}\frac{\partial K}{\partial x_j}\frac{\partial \omega}{\partial x_i} \quad (A.32)$$

Most model constants for SST k- ω model have same values with standard k- ω model. Constants with different values are given below:

Table A.2. Constants for SST k- ω model.

Constant	Value
$\sigma_{kt,1}$	1.176
$\sigma_{kt,2}$	1
$\sigma_{\omega,1}$	2
$\sigma_{\omega,2}$	1.168
α_1	0.31
$\beta_{i,1}$	0.075
$\beta_{i,2}$	0.0828

APPENDIX B: RECREATION OF LEONG'S RESULTS

Leong's study [97] was an important asset for the calculations in Chapter 5. Therefore recreating his results with a reasonable accuracy was an important step in terms of approving the calculation methods for this chapter. For this purpose, before doing the analytical calculations for this chapter, the methodology has been tested by recalculating Leong's work and comparing the results to his original results. During the calculations, thermal conductivity of the nanofluid is taken from Leong's study, which is based on the set of experimental results reported by Eastman *et al.* [93]. As underlined before in Section 2.6., these results differ significantly from Maxwell method calculation results. The results for Nusselt Number and Prandtl Number calculations are presented in Figure B.1 and B.2 respectively. It can be easily observed that the results show significant accuracy in terms of compliance with Leong's results for both cases. The maximum deviation is calculated as 1.257% in Nusselt number calculation, and 2.738% in Prandtl number calculation.

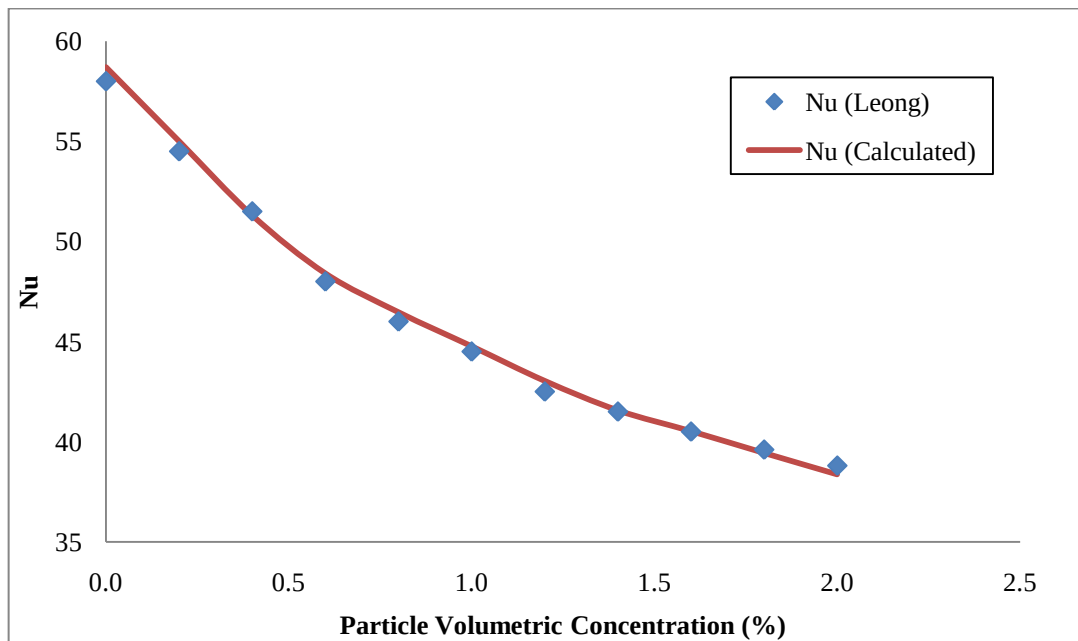


Figure B.1. Nusselt number comparison for Leong's study.

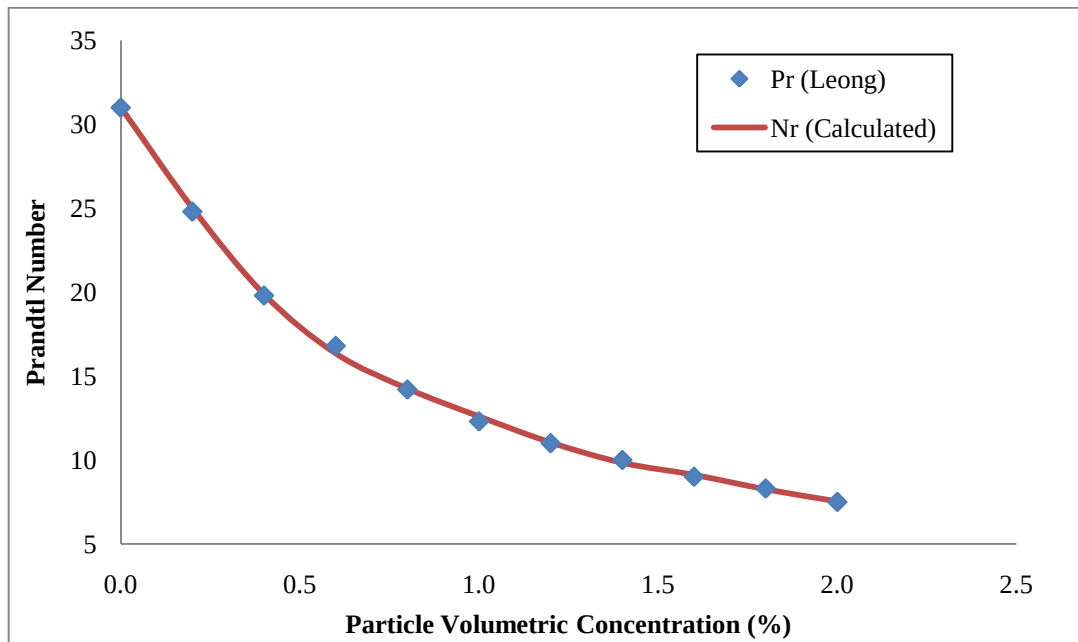


Figure B.2. Prandtl number comparison for Leong's study.

Leong reported in his study, that he has found for air side Reynolds number of 6000 and liquid side Reynolds number of 5000 a maximum frontal area reduction of 18.7% for 2% particle volumetric concentration. Using the same Reynolds numbers, the recalculation of the study gives a frontal area reduction of 18.41%. The deviance in calculation of enhancement is found as 1.57% with respect to the enhancement ratios, and 0,244% with respect to overall cooling loads. The change in frontal area reduction with respect to particle volumetric fraction is presented in Figure B.3. It should be noted that the main factor on this extraordinary enhancement is Eastman's experimental results for Cu-EG nanofluid. Using Maxwell Correlation, the maximum thermal performance enhancement at 2% particle fraction will be 0.3% instead of 18.41%. The main reason for the deviation in thermal performance enhancement is accepted as the particle size, which is given as only 4 nm.

Evaluating the small deviance in cooling load, the accuracy of the calculation method is considered as accurate, and it is concluded that it can be used to calculate hexagonal boron nitride and alumina including nanofluids in Chapter 5.

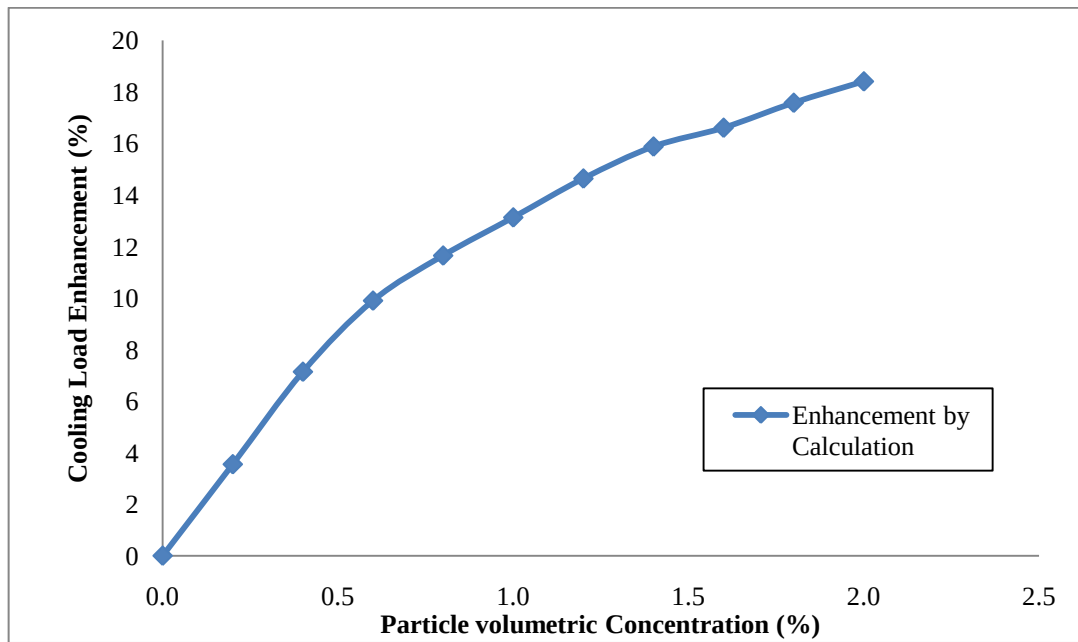


Figure B.3. Cooling load enhancement with respect to particle fraction.

For the radiator analysis, Leong's [97] results in literature have shown very optimistic improvements for copper and ethylene glycol nanofluids. However, calculating nanofluid properties by common correlations in literature gives a significant underestimation with respect to Leong's results. Effective properties for hBN – Water-EG nanofluids calculated by these correlations have decreased the amount of heat transfer increase dramatically. Moreover, it should be noted that water – ethylene glycol mixture is used as base fluid through the radiator analysis in this study in order to simulate a more realistic case, whereas Leong used pure ethylene glycol, which has a lower thermal conductivity. As explained in Section 2.4.2.4 it is known that the effect of nanoparticles on thermal conductivity increases as the thermal conductivity of the base fluid decreases. Therefore, a smaller portion of enhancement is expected through this analysis. Due to this reason, it is observed that despite the significant improvement of fluid thermal properties due to the nanoparticles, the overall heat transfer rate has shown a limited improvement by theoretical and numerical calculations. The resulting improvement is larger than theoretical calculated values, however, it is still considered as insufficient for practical applications.

APPENDIX C: SAMPLE RESULTS

In Appendix C, sample results of analytical calculations and numerical simulations are presented. Data set for Figure 5.4 and 5.5 is presented in Table C.1. The calculation methodology for the results is explained in Chapter 5. Similarly, Nusselt number results for both Al_2O_3 and hBN containing nanofluids with various volumetric concentrations are tabulated in Table C.2. This table includes the results for Dittus-Boelter correlations and numerical analyses for each case.

Table C.1. Nusselt number and thermal performance enhancement values.

Φ (%)	Nusselt Number		Thermal Performance Enhancement	
	Al_2O_3 - Water-EG	hBN - Water-EG	Al_2O_3 - Water-EG	hBN - Water-EG
0.0	47.19	47.19	0	0
0.2	47.24	47.27	0.109	0.13
0.5	47.34	47.41	0.283	0.335
1.0	47.55	47.70	0.6	0.697
2.0	48.13	48.42	1.294	1.476
5.0	50.70	51.40	3.528	3.8715

Table C.2. Nusselt number values for Dittus-Boelter estimations and numerical analyses

Φ (%)	Dittus - Boelter Correlation		Numerical Results	
	Al_2O_3 - Water-EG	hBN - Water-EG	Al_2O_3 - Water-EG	hBN - Water-EG
0.0	47.19	47.19	46.27	46.27
0.2	47.24	47.27	46.33	46.36
0.5	47.34	47.41	46.44	46.53
1.0	47.55	47.70	46.72	47.33
2.0	48.13	48.42	47.46	47.79
5.0	50.70	51.40	50.66	51.45

Table C.3 and Table C.4 include thermal performance enhancement improvement results for a radiator with larger frontal area, using Al_2O_3 and hBN nanofluids respectively. These values are presented as graphs in Figure 5.11 and 5.12.

Table C.3. Thermal enhancement for Al_2O_3 nanofluid in large sized radiator

Φ (%)	$h(\text{air}) = 56$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 100$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 200$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 300$ $\text{W/m}^2\text{K}$
0.0	0	0	0	0
0.2	0.174	0.223	0.272	0.296
0.5	0.454	0.579	0.707	0.77
1.0	0.961	1.227	1.498	1.633
2.0	2.091	2.674	3.269	3.565
5.0	5.776	7.437	9.148	10

Table C.4. Thermal enhancement for hBN nanofluid in large sized radiator

Φ (%)	$h(\text{air}) = 56$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 100$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 200$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 300$ $\text{W/m}^2\text{K}$
0.0	0	0	0	0
0.2	0.209	0.266	0.324	0.353
0.5	0.538	0.686	0.836	0.91
1.0	1.123	1.433	1.748	1.904
2.0	2.392	3.058	3.737	4.075
5.0	6.355	8.189	10.08	11.03

Using experimental results for thermal conductivity enhancement slightly improves thermal performance results. The agreement of correlation approximations and numerical approach for this case are confirmed again by comparing thermal performance enhancement results. These results are presented in Table C.5. Also, recalculated thermal performance enhancement for various air side heat transfer coefficients with experimental data set are represented in Table C.6.

Table C.5. Thermal enhancement by correlations and numerical analysis

Φ (%)	hBN - Water-EG (Correlations)	hBN - Water-EG (Numerical)
0.0	0	0
0.2	0.209	0.266
0.5	0.538	0.686
1.0	1.123	1.433
2.0	2.392	3.058
5.0	6.355	8.189

Table C.6. Thermal enhancement with various boundary conditions

Φ (%)	$h(\text{air}) = 56$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 100$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 200$ $\text{W/m}^2\text{K}$	$h(\text{air}) = 300$ $\text{W/m}^2\text{K}$
0.0	0	0	0	0
0.2	0.1614	0.2413	0.268	0.2886
0.5	0.398	0.528	0.66	0.7093
1.0	0.8332	1.1053	1.3804	1.4844
2.0	1.6882	2.2378	2.7905	2.9956
5.0	4.2632	5.67	7.0698	7.5625

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