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Treball Final de Grau

Enhancement of heat transfer using nanofluids: application to an automotive radiator

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Nanotechnology has been moving a little faster than I expected, virtual reality a little slower.

Nick Bostrom

En primer lloc vull agrair als meus pares, la meva germana i a l'Andrea el suport i els ànims que he rebut durant aquests quatre anys quan més ho necessitava.

En segon lloc, vull agrair al meu tutor Ricard Torres, la seva ajuda en tot moment, els consells i la plena disposició a resoldre qualsevol petit dubte en la confecció del treball.

Finalment, dono les gràcies als companys de classe amb els quals he tingut grans vivències i han fet tot més amè.

CONTENTS

SUMMARY

This final project aims to carry out a bibliographic research on nanofluids, included within nanotechnology, one of the most recent sciences and with the greatest future projection. Given the good thermal characteristics that nanofluids exhibit (they improve heat transfer), they are currently being proposed to use them as thermal fluids. One of these uses can be antifreeze in automotive radiators, which will be verified in this work.

To verify this, ANSYS® simulation program has been used, specifically its Fluent module. Two simulations have been performed, based on a previously designed 3D model that represents an automotive radiator, since the limitations of the software version used (ANSYS® Student version) do not allow the design of a completely faithful model to reality. The same conditions have been established for the two simulations and only the circulating fluid inside the radiator has been varied. In the first case, the fluid is a mixture of ethylene glycol and water (more common fluid nowadays) and in the second, a nanofluid has been used. Finally, the obtained results have been presented and a comparison between simulations has been made that allows an assessment on the convenience of applying nanofluids to automotive radiators. Although they exhibit great thermal properties, stability and price are two great obstacles to overcome.

Keywords: nanofluids, ANSYS® Fluent, heat transfer, nanotechnology

RESUM

Aquest treball fi de grau pretén fer una recerca bibliogràfica dels nanofluids[1], englobats dintre de la nanotecnologia, una de les ciències més recents i amb més projecció de futur. Donades les bones característiques tèrmiques que els nanofluids exhibeixen (milloren la transferència de calor), actualment s'està proposant la seva utilització com a fluids tèrmics. En aquest treball es vol comprovar si un d'aquests usos podria ser el d'anticongelant a un radiador d'automoció.

Per comprovar-ho s'ha utilitzat el programa de simulació ANSYS®, concretament el seu mòdul Fluent. S'han realitzat dues simulacions partint d'un model en 3D, prèviament dissenyat, que representa un radiador d'automoció, ja que les limitacions de la versió de programari utilitzat (ANSYS® Student version) no permeten dissenyar un model totalment fidel a la realitat. S'han establert les mateixes condicions per a les dues simulacions i només s'ha variat el fluid que circula per l'interior del radiador. En el primer cas es tracta d'una mescla d'etilenglicol i aigua (fluid més comú avui dia) i en el segon s'ha utilitzat un nanofluid. Finalment, s'han presentat els resultats obtinguts i s'ha fet una comparativa entre simulacions que permet fer un judici de valor sobre la conveniència de la aplicació dels nanofluids en els radiadors d'automoció. Tot i que exhibeixen grans propietats tèrmiques, la estabilitat i el preu són dos grans obstacles a superar.

Paraules clau: nanofluids, ANSYS® Fluent, transferència de calor, nanotecnologia

[1] Un nanofluid és una solució formada per un fluid que s'utilitza com a base en el qual hi ha dispersades partícules de mida nanomètrica.

1. INTRODUCTION

Heat transfer surrounds us every second of our lives. Some heat exchanges are more important than others and require to be more optimized, such as the heat transfer in the industry, where profit is the main objective.

To improve this exchange, many options are eligible: change the dimensions of the exchanger, layout of the pipes, addition of fins… These options are related to the exchanger itself, but improvements can also be made in the fluids used to heat or refrigerate.

The most common solution, related to fluids, is to use well known ones like water or thermal oils (in case of higher needs of temperature). Nevertheless, growing sciences have carried and are carrying out many solutions that can be applicable to areas like heat exchange. One of these sciences is nanotechnology.

1.1. NANOTECHNOLOGY

Nanotechnology is a science that embraces the study and application of particles between 1 and 100 nanometres (commonly known as nanoparticles). Sometimes it's difficult to have a clear idea of which size ranges are we talking about. To help so, here are two examples: a sheet of paper is about a 100,000 nm thick and a human hair is approximately 80,000 – 100,000 nm wide.

Compared to other ancient sciences, nanotechnology is very recent. In 1959, Richard Feynman gave what is considered the first lecture on technology and engineering at the atomic scale: "There's Plenty of Room at the Bottom" at an American Physical Society meeting at Caltech, even though at that time it wasn't known as nanotechnology. It was in 1974 when Norio Taniguchi from Tokyo University used the word "Nanotechnology" to describe a set of studies and techniques. Finally, in 1981, Gerd Binning and Henrich Rohrer developed the scanning tunnelling microscope and since this moment, the nanotechnology era started.

Nanotechnology is more than what a first sight of it can seem. It's not only about working at smaller dimensions but understand and take advantage of phenomena that occur naturally when matter is organized at the nanoscale.

1.1.1. THE NANOSCALE

One of the most important effects in nanoparticles are quantum effects. At this point classical physics cannot explain what happens and quantum mechanics are required. Quantum effects appear when particles are in the nanoscale range and have influence in the behaviour and final properties such as thermal, electrical, mechanical, chemical, optical and magnetic. This is a powerful tool because a small change in particle size can lead to a change in its properties.

In addition, at the nanoscale is where the major part of biology happens. This fact is helping nanotechnology to grow up because of the research on this field (nanomedicine). Even though nanomedicine is far less developed than medicine, next years are promising about what nanomedicine can contribute to us; because of the particle size, nanomedicine is much more targeted towards the tissue that requires the medication.

And finally, but not less important, it is the surface area that nanoscale materials have compared to large scale materials. If the surface to volume ratio changes, reactivity also varies because a bigger amount of material is exposed ready to react (*Figure 1*). This improvement of surface area in nanostructured materials results in the development of better catalysts, where surface area is very important. Nowadays one third of global catalyst markets are influenced by nanoparticles and their benefits.

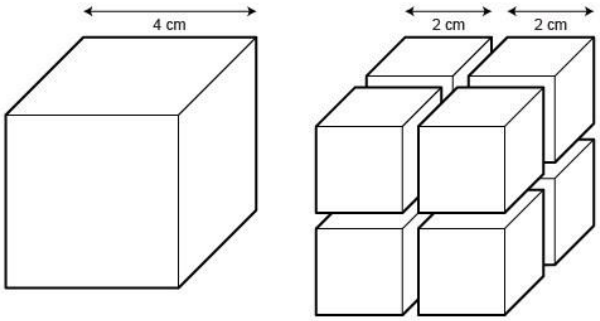

Figure 1. Surface to volume ratio (via whatisnanomedicine.com)

If the first cube is taken and its area is calculated, results are: (4 cm x 4 cm x 6 faces) = 96 cm^2.

On the other hand, for the second cube:

- For one cube: (2 cm x 2 cm x 6 faces) = 24 cm^2.
- Total surface area: (24 cm^2 x 8 cubes) = 192 cm^2.

For this specific case, taking the same volume but cutting the cube in smaller ones causes an increase in surface area of a 100%. This, applied to thousands of millions of particles, give to nanomaterials their unique characteristics.

1.2. **COLLOIDAL SYSTEMS**

When talking about nanofluids is important to know that they are colloidal systems and, therefore, some of their characteristics come directly from them. Matter can be in four different states depending on the conditions of pressure and temperature (solid, liquid, gas or plasma). These different states can form substances, which in turn can be pure or mixed with other substances, making which is known as solutions.

Solutions can be either homogeneous or heterogenous depending on whether the properties are the same or different point to point. In a homogeneous system the intensive

properties (density, melting point, boiling point, etc.) are the same in all its points whereas in a heterogeneous system, intensive properties change.

The term colloid comes from the Greek word "κολλα" which means glue. A colloid is a solution that has particles dispersed (between 1 – 1,000 nanometres and called dispersed phase or discontinuous phase) in another substance called dispersant phase, dispersion medium or continuous phase. The dispersed particles can remain evenly distributed throughout the solution and do not settle to the bottom with the passage of time. Related to the types of solutions, colloids turn out to be heterogeneous because suspended particles retain its identity in suspension.

The physical dimensions of the particles (shape and size) are the most important characteristic of the colloidal systems and by extension, of the particles that form them. The thermophysical properties of the solution and other properties such as the behavior of the aggregates or the surface area depend on them. However, there are other characteristics of the colloids that must be controlled so that the properties of the prepared solutions are adjusted to the desired ones. Below are some of them.

1.2.1. PARTICLE AGGREGATE

It is a proven fact that small particles of a suspension tend to join due to the force between particles and thus form larger structures called aggregates. It is worth noting that in the case of nanofluids there are two types of aggregates. The first type is formed by the aggregation of nanoparticles in dry powder form and the only way to separate the aggregates is to suspend the particles in a fluid by ultrasound or high shear (preparation of a nanofluid). The second type of aggregates (Timofeeva et al., 2009), are formed by the suspension of isolated crystalline nanoparticles and a few aggregates of nanoparticles (small clusters), thus forming large clusters. This type of aggregate is more difficult to break, and, in many cases, it is necessary to use more than one method (e.g., surfactant, high shear or ultrasonication) to break the aggregate. However, in most cases the presence of small isolated aggregates is inevitable.

1.2.2. POLYDISPERSITY

When working with dispersed systems is important to determine the polydispersity to know the amplitude of the molecular weight distribution and therefore know the variety of particles that

make up the system. If the set of particles that make up a system are very different, assume that they have the same size is a serious error that can greatly affect the final characteristics. That is why polydispersity is defined, which can vary between 0 and 1. When its value is 0, it is known as monodisperse system and all the particles have the same size. On the contrary, when its value is 1, the system is polydisperse and there is a great variety of sizes (Everett, 1998).

1.2.3. ZETA POTENTIAL

All particles have an electrical double layer, which consists of two parts: an inner region where the ions are strongly linked (stern layer) and another more external where the ions are not so strongly associated (diffuse layer). This last layer is very important since it is the one that delimits the particle as a single entity. The potential measured in this layer is the so-called zeta potential and is measured in millivolts (mV). The importance of this phenomenon is great because it allows to determine important characteristics in colloids such as stability or flow behaviour. The larger the zeta potential, the more stable the particle, since the forces of repulsion between particles will be higher than those of attraction. According to Muller (1996), a value of +60 mV indicates a very good stability, between 30 and 60 mV physical stability is shown and for values lower than 20 mV unwanted agglomeration phenomena begin to emerge.

1.2.4. BROWNIAN MOTION

It is the random and erratic movement of microscopic particles suspended in a fluid, caused by the collisions of molecules with the surrounding environment. This movement is independent of the nature of the colloid but depends on the viscosity of the solution and the size of the particles; the smaller the size and the lower the viscosity, the faster the movement.

1.2.5. TYNDALL EFFECT

This physical phenomenon is a simple and quick way to check if a solution is colloidal, since in some cases the scattered particles may not be visible to the naked eye and the solution may appear homogeneous. When the light passes through a homogeneous solution, the dissolved particles are so small that they do not deflect the light, however, in a colloidal solution, the light finds particles in its path and cannot follow a straight line, thereby that scatters in all directions.

As shown in *Figure 2*, when the beam of light passes through a homogeneous solution it follows a straight path and therefore cannot be seen. When this same beam of light passes through the second container, which contains a colloidal solution, the light is scattered, and the path of the laser is observed.

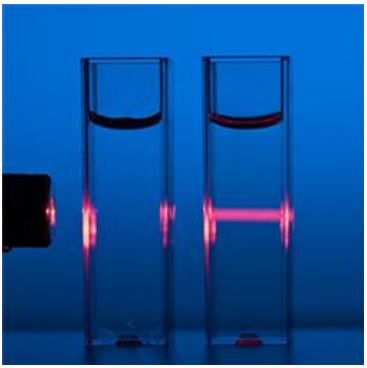

Figure 2. Light path through different solutions (via ilustracionmedica.wordpress.com).

2. OBJECTIVES

The aim of this project is to carry out a bibliographic review of the nanofluids and to try to see the possible improvement they can produce in an automotive radiator (cross flow heat exchanger) using the ANSYS ® Fluent simulation program.

In the bibliographic review will be treated aspects such as preparation or characterization of nanofluids and others of vital importance for its possible application to the heat exchange as its properties, prices and advantages and disadvantages.

In the second part, once the nanofluids are known in depth, a simulation will be carried out to see all the aforementioned advantages or disadvantages in a numerical way and thus be able to draw conclusions about the possibility or not of using the nanofluids as refrigerant fluids.

3. NANOFLUIDS

Nanofluids are colloidal suspensions of nanosized solid particles in a liquid, made to improve thermal properties of the base fluid. Commonly used heat transfer fluids (e.g. ethylene glycol, water, Freons, oils, etc) have lower thermal conductivity than nanofluids. As a colloidal suspension, two phases coexist: nanoparticles in solid phase and the base fluid in liquid. The kind of nanoparticles that can be used is very wide; they can be metals (e.g. copper, nickel, aluminium), oxides (e.g. alumina, titanium) or other elements such as carbon nanotubes, graphene or silicon carbides.

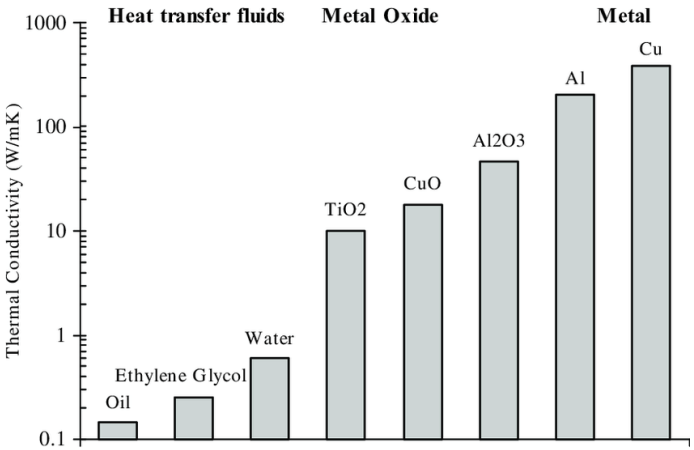

Figure 3. Comparison of thermal conductivities [(1)].

As shown in *Figure 3,* the differences between conventional heat transfer fluids and metals or metal oxides are huge when talking about thermal conductivity. While metal oxides are an order of magnitude higher, metals are two. Although what is really important is that the nanoparticle and fluid mixture have a high conductivity, that the particle has it by itself is already a good indicator.

The first organisation who introduced the term “nanofluids” was the National Argonne Laboratory, a science and engineering research national laboratory operated by the University of Chicago. In first place it was demonstrated that the dispersion of some oxide nanoparticles (Al_2O_3, SiO_2 and TiO_2) in water improved heat properties (Masuda et al., 1993). Two years later this was extended to more fluids apart from water (Choi & Eastman et al., 1995).

So many are nanofluids advantages that the number of research and publications has only grown exponentially over the years, as shown in *Figure 4*. It is a huge field to do research, since all the properties of nanofluids (thermal, electrical, magnetic, optical, etc.) must be analysed under different conditions. Heat exchange fluids are widely used both in the industry and in daily life objects, clear examples are the automotive industry or electronics. The appearance of nanofluids has opened a new (theoretically) more efficient way to exchange heat and the interest in taking advantage of this fact is reflected in the growing number of investigations.

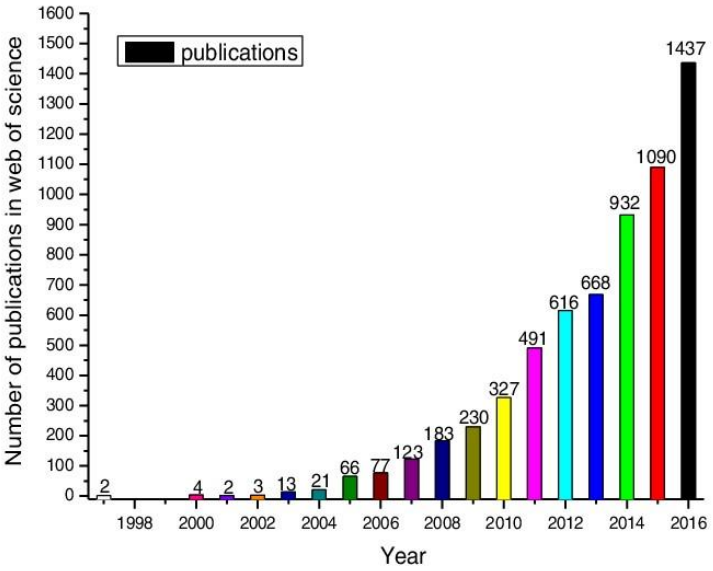

Figure 4. Number of publications with the word “nanofluid” or “nanofluids” in the title, retrieved by "web of science" page [(2)].

However, all the advantages of nanofluids will not be widely usable if the production cost of these is so high that it does not compensate the replacement of the current used fluids. Given the complexity and variability that nanoparticle systems present in their preparation, cost

estimates have been attempted as close as possible to reality. A proposed solution is the use of simple *Equations 1 and 2*:

$$C_T = C_{Nanop} + C_{Base} \left[\frac{EUR}{dm^3}\right] \quad \textbf{(Eq. 1)}$$

$$C_{Nanop} = \frac{C_u \cdot \rho \cdot V}{0.001} + C_{Other} \left[\frac{EUR}{dm^3}\right] \quad \textbf{(Eq. 2)}$$

The total cost of a nanofluid is the sum of the cost of the nanoparticles and the cost of the base fluid, expressed in euros / litre (*Equation 1*). The base fluid is obtained directly and therefore its price is that of the formula. On the other hand, the price of nanoparticles depends on other factors that are broken down in *Equation 2*. The term C_u refers to the unit cost of buying the nanoparticles [EUR / g], ρ is the density of the liquid and V is the volume. The term "other" refers to additional costs related to the method of preparation of the solution, considering among other things the energy spent and the cost of stabilizing the solution. The most economical and least energy consuming systems are those based on surfactants, although at high temperatures they cannot be used. *Table 1* shows the prices of different nanofluids and how an increase in concentration affects the cost.

Table 1. Prices of different nanofluids and their variation with concentration [7].

Nanofluid	Nanoparticle size [nm]	Concentration [%vol]	Gross cost of 1 L [EUR]
Pure DI water	-	-	0.07
TiO_2	4 - 8	0.04	3.03
		0.07	5.26
		0.1	7.48
Ag	< 100 nm	0.04	223.47
		0.07	391.01
		0.1	558.54

(a) Gross prices include 23% VAT rate

3.1. CHARACTERIZATION

Before preparing nanofluids many actions should be planned; many alternatives are eligible in each step in its preparation and every single one has a different impact in the final nanofluid. Some important features are: thermal stability, dispersibility in diverse media and chemical compatibility. Moreover, they are connected between each other.

Also, properties are important when talking about nanofluids, because they are the main claim for their introduction as refrigerant fluids. Like any innovative concept, many studies are carried out before being able to postulate any finding as true. However, in the study of nanofluids there is a wide range of possibilities, since only by changing a little the concentration, the temperature at which it works, the shape, size or type of nanoparticles, the results obtained are very different. That is why some studies have found opposite tendencies in terms of the behaviour of nanofluids when certain parameters vary. In the end, there has always been an attempt to reach a consensus among researchers to avoid contradictions in studies. Below are some important features of nanofluids:

3.1.1. THERMAL STABILITY

Nanoparticles are metastable systems, that is, they are systems that have several states of equilibrium but remain in a state of weak equilibrium for a considerable period of time. However, the system can suffer external disturbances that lead it to move towards a state of strongly stable equilibrium. If one of these systems is represented by its potential energy, the metastable state corresponds to a local minimum of energy. To reach the most stable state, which corresponds to the absolute minimum of energy, it will be necessary to communicate an activation energy to the system. As shown in *Figure 5*, state 1 corresponds to a metastable state that tends to reach stable state 3. To achieve this, first needs to pass through unstable state 2.

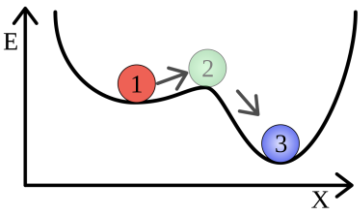

Figure 5. Stability states (via Wikipedia).

Analogously, nanoparticles can be represented in a metastable system, as represented in *Figure 6*. In this case, nanoparticles are in an intermediate state between the molecules / atoms and the bulk agents and it's possible to convert from one to another by physical or chemical ways.

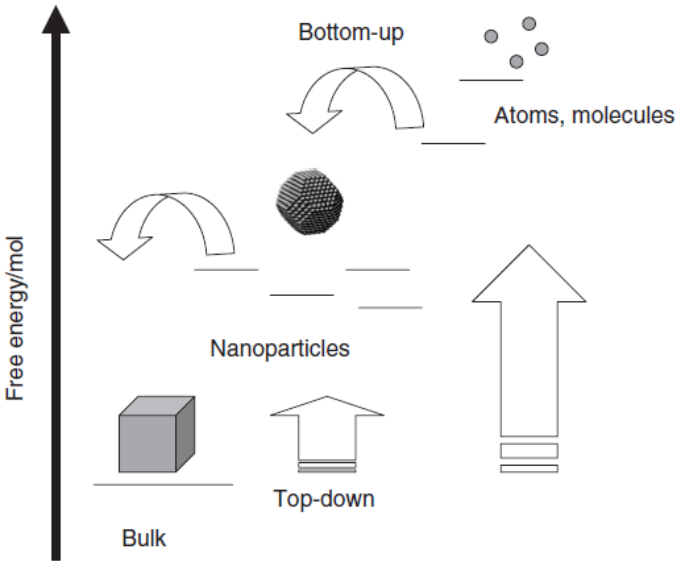

Figure 6. Different approaches to nanoparticles depending on free energy [3].

As can be seen in *Figure 6*, transformation from atoms / molecules to nanoparticles is called bottom-up and the process to go from bulk to nanoparticles is called top-down. Between atoms / molecules and nanoparticles there is an intermediate step called clusters and analogously between bulk and nanoparticles are the powders. Looking at the graph, the processes that involve lowering free energy are spontaneous. Therefore, it will be the passage of atoms / molecules to nanoparticles and the passage of nanoparticles to bulk. However, it should be noted that the fact that they are spontaneous does not mean that they are instantaneous, since for example the passage from nanoparticles to bulk could take place at infinite time. This can be compared to the stability of graphite carbon and diamond. Although graphite is

thermodynamically more stable, diamond does not spontaneously convert to carbon, since the transformation kinetics are very slow at normal pressure and temperature.

3.1.2. DISPERSABILITY IN DIVERSE MEDIA

Nanoparticles are composed mainly of two parts: the core and the shell. The core of a nanoparticle can be ceramic, polymeric or metallic and the shell (which is very thin compared to the core) can be ionic, polymeric, molecular, ceramic or metallic. However, they are usually composed of a ceramic or metallic core and a molecular shell.

In terms of functionality, the properties of the nanoparticles fall on the core while the function of the shell is mainly protective. Despite this, the shell may have other important functions such as the luminescence of the particles. Also, the shell is the part that determines the capacity and ease of dispersion of the nanoparticle in a medium, according to its chemical nature.

Taking as an example the most common shell (molecular), thanks to certain atoms or some groups, the shell has chemical affinity with the core. For a metallic gold nanoparticle, the metal can be bound with a thiolate sulphide atom, covering the entire surface of the core with multiple bonds. In this case, the shell is called a protective monolayer and the bonds that make it provide thermal stability to the nanoparticle.

The part of the shell that is responsible for interacting with the medium or solvent in which the nanoparticle is located is the functional group (*Figure 7*). A positive interaction between functional group and environment will cause the desired effect, the dispersion of the particles. An example of this positive interaction would be if a nanoparticle wants to be dispersed in water; the functional group of tail should be hydrophilic so that the interaction with water is positive. On the other hand, if nanoparticles are going to be dispersed in non-polar substances such as benzene, the functional group must be hydrophobic.

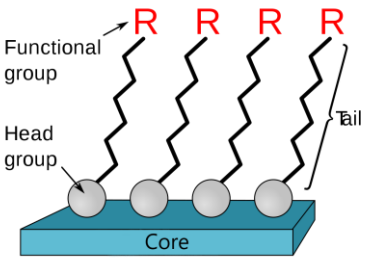

Figure 7. Representation of the interaction between the core and the medium (via Wikipedia).

However, the shell does not have to be a molecule, it can be a part of the core like in silica nanoparticles, where the surface of the core is a layer of hydroxyl groups that allow the nanoparticles to be suspended in water.

An important feature of the functional group is that it can change its character depending on the medium. This affects groups like -COOH, $-NH_2$, and -OH where the pH changes of the medium can significantly affect those groups and, therefore, the charge in the nanoparticle surface. These changes also affect the zeta potential, which in turn has a direct effect on the properties.

All the core-shell properties explained in this section have been applied to spherical nanoparticles, but in the same way they can be reflected in other forms such as nanorods, nanotubes or nanoshells, where a shell is applied so that the particle is dispersed in the solution.

3.1.3. CHEMICAL COMPATIBILITY

When working with nanoparticles it is possible that at some time the core or the shell are sensitive to a chemical substance. Since this is an unwanted situation it is possible to modify the shell so that the chemical does not have access to the shell and / or the shell does not react. This process is carried out after synthesizing the nanoparticle, it is known as ligand exchange and as its name suggests, it consists of exchanging all the molecules that form the monolayer for others.

3.1.4. THERMAL CONDUCTIVITY

This property is considered as the most important of a fluid that is going to be used as a heat transfer fluid, since it is related to the heat transfer coefficient (h), which in the end is an indicator of the system's performance. Thermal conductivity is the transport of energy (in the form of heat) through a body with mass because of a temperature gradient. It is expressed by the symbol k or λ and its units are W/(m·K). In nanofluids, and therefore in suspensions, the thermal conductivity depends on several factors. On the part of the nanoparticles, it depends on size, shape, concentration and thermal conductivity of these. It also depends on the type of base fluid, the global temperature of the nanofluid and the preparation technique.

The thermal conductivity of a nanofluid is better than the base fluid one, due to the better conductivity of the particles that are dispersed. Therefore, a higher concentration of particles explains the increase in conductivity. The Brownian movement of the particles also has a lot to do, since these random and repeated collisions between particles improve the thermal conductivity. In addition, this effect is even greater when the temperature is higher.

Therefore, an increase in temperature will also be beneficial for the conductivity since, by increasing the Brownian motion, the contribution of the microconvection in heat transfer also increases.

Particle size is also important, being that, as has been stated previously, the smaller the size, the higher the surface area / volume ratio and therefore the higher the conductivity. And as for the shape, numerous studies (Xie et al. (2002), Hwang et al. (2006)) showed that cylindrical forms presented a higher improvement than the spherical ones, despite their higher average size.

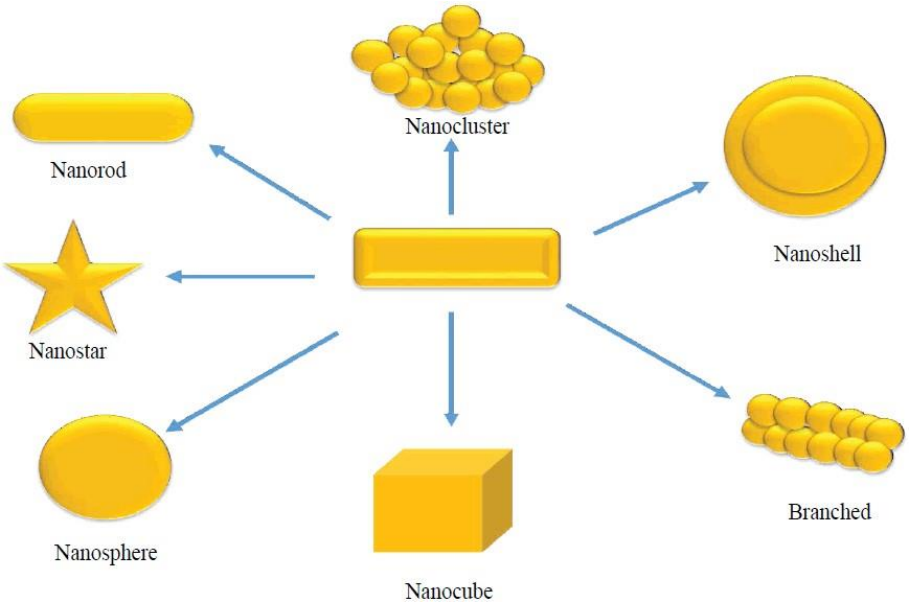

Figure 11. Different nanoparticles shapes [12].

3.1.5. VISCOSITY

Viscosity is the resistance of the molecules that make up a liquid to separate from each other, that is, the opposition of a fluid to be deformed; this opposition is due to the adhesion forces that molecules of a liquid or fluid have with other molecules. It is expressed by the symbol μ or η and its units are usually cP or Pa·s. In nanofluids, viscosity is affected mainly by temperature, particle size, concentration and the method of preparation.

It has been shown that an increase in temperature causes a decrease in the viscosity of the nanofluid. In addition, viscosity is strongly influenced by the shape of the nanoparticle, showing cylinders the highest viscosity for the same volume fraction and spheres the smallest. It should also be noted that a higher concentration of particles implies a higher viscosity.

3.1.6. DENSITY

Density is defined as the amount of mass per unit volume, symbolized by the letter ρ and expressed in kg/m^3. Unlike the other properties previously exposed, density is only strongly

affected by the material that makes up the nanoparticles used. As density of solids is greater than that of liquids, the density of a nanofluid will increase when the concentration of nanoparticles does. And just as it happens with viscosity, when temperature increases, density lowers.

3.1.7. SPECIFIC HEAT

Specific heat is the amount of heat that must be supplied to a unit of mass of a substance to raise its temperature one unit. It is expressed in J/(kg·K) and by the symbol C_p. In general, specific heat decreases with the addition of nanoparticles. However, with this property there is a contradiction. Shahrul et al. (2014) observed the opposite tendency, that by adding more nanoparticles to the system, their specific heat increased. Apart from this event, specific heat depends mainly on the characteristics of nanoparticles, such as size, shape, temperature and material. Also, in this section there is some discussion since after different studies, temperature and particle size showed contradictory conclusions. However, some researchers have concluded that specific heat increases with increasing particle diameter.

3.2. NANOPARTICLES PREPARATION METHODS

To prepare nanofluids two components are required: nanoparticles and a base fluid. Both, the preparation of the nanoparticles and the preparation of the nanofluid are critical points that must be thoroughly studied before being carried out. The fluid normally does not require any exhaustive preparation and is easy to obtain.

The keys to nanoparticles preparation are the suppression of the aggregation, the formation of high-degree supersaturation in narrow time or space and a controlled monodisperse growth or Ostwald ripening (diffusion-controlled growth).

There are many ways to prepare nanoparticles, depending on the nature of the particle itself (metallic, polymeric ...) and the desired characteristics of the final nanofluid. Mainly there are three types of methods to synthesize nanoparticles: physical, biological or chemical methods and each of them offers a wide variety of techniques. Since a compilation of all the methods would give to do a work only of that, below are two examples. The first, a method of metal

particles, as they have the highest conductivity and therefore are the most interesting in this project. And the other with polymeric particles, because they have the greatest future projection given their broad fields of application and the growing interest in polymeric materials.

3.2.1. METALLIC PARTICLES: INERT GAS CONDENSATION

This technique allows to obtain metal nanoparticles from a solid metal fragment. Using resistive heating, the metal evaporates inside a chamber filled with inert gas at low pressure. The generated vapour moves to a cooling zone thanks to convective flow and diffusion and particles are collected for subsequent consolidation, usually by deposition on the cold surface. Finally, the particles pass to a collector and later to a compaction unit, from where the nanoparticles will be ready to be used (Pokropivny et al., 2007). *Figure 8* schematically represents this process.

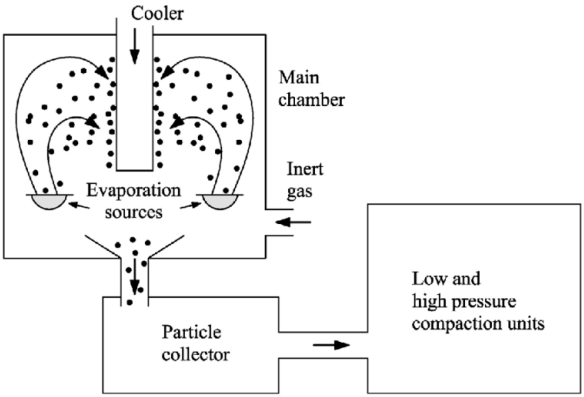

Figure 8. Inert gas condensation system [4].

3.2.2. POLYMERIC PARTICLES: SOLVENT EVAPORATION

This technique was the first that was used to prepare polymeric nanoparticles and is still used due to its simplicity. It consists in mixing a continuous (aqueous) phase with a drug + polymer solution in an organic solvent, normally ethyl acetate. This mixture can form different types of emulsion, such as oil-in-water (o/w) or others more complex as (water-in-oil)-in-water,

that by agitation become nanoparticle suspensions. In the last step the solvent is evaporated, by magnetic stirring at room temperature or under reduced pressure conditions. After this, solidified nanoparticles are obtained, collected by ultracentrifugation, washed to remove substances such as surfactants and finally lyophilized to obtain a dry product (Tyagi & Pandey, 2016). *Figure 9* shows process.

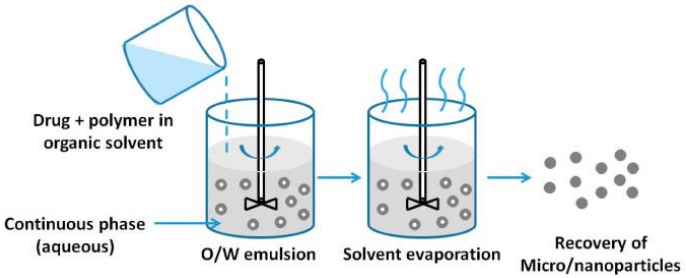

Figure 9. Solvent evaporation procedure [5].

3.3. NANOFLUIDS PREPARATION METHODS

The preparation of a nanofluid is not as easy as put together many particles and a base fluid. Preparation is a critical step of the process because depending on the method used, thermal conductivity and viscosity are very affected. There many requirements for a nanofluid to be accomplished such as uniformity, stability, durability, low agglomeration and chemical stability. Achieve all these requirements develop many concerns on preparing nanofluids, mostly: dispersion method, type of mixture, dispersion medium / phase, thermal stability, chemical compatibility and preparation techniques.

Mainly, the preparation of nanofluids from nanoparticles is divided into two methods: single-step method and two-step method.

3.3.1. TWO-STEP METHOD

The two-step method (Paul et al., 2011; Yu et al., 2011) is the most widely used to produce nanofluids and the best to mass productions because nanopowder synthesis is well known at industrial scale. As its name stands, it is composed of two steps. In the first step, nanoparticles

are produced as dry powders by either physical or chemical ways. Afterwards, the powder is dispersed in a fluid helped by external forces like intensive magnetic force agitation, ultrasonic agitation (Goharshadi et al., 2009), high-shear mixing (Pak & Cho, 1998; Wen & Ding, 2005), homogenizing or ball milling. Other dispersion possibilities involve the addition of dispersants or adjust the pH value. The aim of using external forces is to breakdown nanoparticle aggregations and with dispersants or pH adjusting, the objective is to avoid re-aggregation.

Due to the aggregation tendency the nanoparticles have, usually, to the resultant nanofluid after the two-step method, surfactants are added to reach a certain level of stability. Nevertheless, surfactants don't work well under high temperatures and therefore are not always effective. In addition, according to few researches, the addition of surfactants during the preparation stage considerably reduces the thermal performance of the solution.

To solve these problems with the stability of the solution, several procedures were developed, including a new method of preparation: the single-step method.

3.3.2. SINGLE-STEP METHOD

Single-step method avoids the stability problems of the two-step method, combining the production of nanoparticles and its dispersion into a base fluid in a single step (Eastman et al., 2001). Trying to face these problems, a big research was made, and many variants of single-step process came out. One of these techniques was developed by Akoh et al. (1978). Named VEROS (Vacuum Evaporation onto a Running Oil Substrate) it involves condensing nanophase powders from the vapor phase directly. However, this method has difficulties in separating the nanoparticles from the fluids to make dry powders or bulk materials.

Years after, Eastman et al. (1997) modified VEROS process to overcome these issues. Through a direct evaporation-condensation process they achieved a uniform distribution of particles in a fluid. With this VEROS modified process they managed to increase a 40% the thermal conductivity of ethylene glycol (the base liquid) just adding Cu nanoparticles in a 0,3% concentration in volume. Nevertheless, this process brought out new issues with him: it wasn't suitable for large-scale productions and was only applicable to low-vapor-pressure liquids.

Zhu et al. in 2004 developed a brand-new one-step method with chemical base instead of physical. They claimed its process to be faster and cheaper. This process produces a Cu /

ethylene glycol nanofluid by reducing $CuSO_4 \cdot 5\ H_2O$ with $NaH_2PO_2 \cdot H_2O$ under microwave irradiation.

A year later, Lo et al. developed Submerged Arc Nanoparticles Synthesis System (SANSS), to prepare metal particle based nanofluids. This process involves vaporizing a pure metal rod by a submerged arc in deionized liquid under a controlled vacuum environment, followed by rapid quenching of the vaporized metal gas by a cooling system, thus forming nanocrystalline powders.

Figure 10 is an example of the one-step method. The raw material is heated and evaporated in a heated crucible that is located inside a rotating disk. The centrifugal force causes a flow of base liquid as if it were a film around the entire disc. When the vapour produced touches this thin layer of liquid, it condenses in the form of nanoparticles that in turn remain in the liquid and therefore the nanofluid is obtained directly.

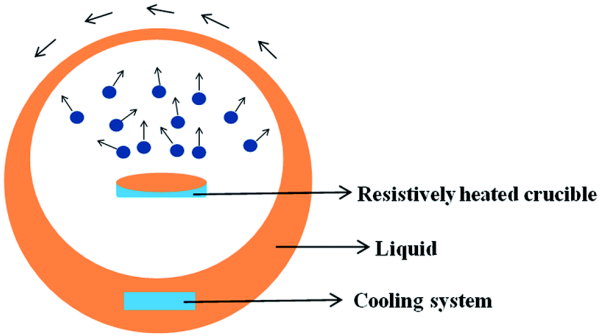

Figure 10. Direct evaporation technique [6].

To sum up, two-step method is suitable for mass productions even though agglomeration issues are its main drawback. On the other side, single-step method deals with agglomeration issues but requires that base fluid must have low vapor pressure and is not recommended for large-scale productions.

3.4. **BASE FLUIDS AND PARTICLES COMMONLY USED**

The production of nanofluids is not restricted to a single type of nanofluid, since both the particles and the base fluid can be chosen from a wide range of possibilities.

The base fluid is usually water, because it is a universal and cheap solvent. It coincides with the fact that water is also the most commonly used heat transfer fluid. Normally, different types of glycols (MEG, DEG, TEG, propylene…) are also added to increase the boiling and freezing point of the mixture and thus improve the properties. In some cases, when high heat transfer capacities are required, oils are used. There are also some innovations regarding available base fluids to disperse the nanoparticles. An example is the use of refrigerants as base fluids, known as nanorefrigerants and another is the dispersion of nanoparticles in PCM (phase change materials), called the resulting material as NEPCM (nano-enhanced PCM).

For nanoparticle selection, the most important criterion is the capacity of heat transfer that they possess. Since the objective of a nanofluid is the improvement of heat transfer, it does not make sense to use nanoparticles whose heat transfer capacity is like those of the fluid already used. Therefore, the most commonly used nanoparticles are metals (e.g., Cu, Ag, Fe), oxides (e.g., CuO, TiO_2, Al_2O_3), alloys (e.g., Ag-Cu, Fe-Ni, Cu-Zn), metal carbides (e.g., SiC, ZrC, B_4C), multielement oxides (e.g., $ZnFe_2O_4$), metal nitrides (e.g., TiN, SiN, AlN) or carbon based materials (e.g., carbon nanotubes, graphene, diamond).

There is even an extra possibility, the manufacture of so-called hybrid nanofluids. This type of nanofluids are characterized by being made of a combination of more than one type of nanoparticles suspended in a base fluid. The goal is to further improve the properties that a standard nanofluid provide.

3.5. **ADVANTAGES AND DISADVANTAGES**

The most important advantage of nanofluids, which is also related with the aim of this project, is the enhancement of thermal conductivity. This is possible thanks to another advantage of nanofluids: their properties are adjustable to any specific case required just modifying parameters like concentration, particle size or choosing other nanoparticles. Nevertheless, there are other important advantages:

- As explained before, nanoparticles have bigger surface to volume ratio compared to other particles, which gives them more heat transfer surface area.
- Using nanosized particles instead of bigger ones, decreases the possibility of clogging.
- Compared to base liquid, less pumping power is required to achieve same heat transfer due to predominant Brownian motion of particles. Roughly, the Brownian motion describes the erratic and random movement of a particle located in a fluid. This kind of movement is inducted by the surrounding fluid because of continuous crashes between particles.
- The collision and interaction among particles are intensified.

Even though all these advantages sound very promising, also is important to know the disadvantages of nanofluids. One of the most important disadvantages relies in their obtaining mode. When particles are added to a base fluid, viscosity of the mix increases, developing a higher pressure drop and requiring higher power of pumping. Depending on the system where the nanofluid is applied, a redesign of pumping system can be mandatory. Other disadvantages are:

- Lower specific heat compared to base fluids. This is exactly the opposite of desired, since a high specific heat is required to remove the maximum amount of heat. This limits the use of nanofluids.
- Production cost can be a critical disadvantage in some applications being that necessary equipment to prepare nanofluids is quite expensive.
- Poor long-term stability of suspension: strong Van der Walls forces appear between nanoparticles, forming a non-homogeneous suspension that in rarely cases can lead to clogging in flow paths. Surfactants are a well-known solution to stability issues.

3.6. **SAFETY**

Safety is always an aspect to consider in the workplace, and therefore, the production or use of nanofluids would not be less. Since the development of nanomaterials is relatively recent, the effects and hazards to health have not yet been fully studied. The main danger when

working with nanoparticles is toxicity hazard, although under certain conditions dust explosion may also be important.

When talking about a dust explosion, there are five key aspects that contribute to the explosion taking place: ignition, dispersion, confinement, fuel and oxygen (explosion pentagon). This usually happens when nanoparticles are subjected to processes such as sanding, cleaning, grinding, drilling or mixing; the probability of suffering an explosion increases mainly due to the increase in the specific surface area that the particles undergo when reduced to the nanosize. A larger surface means a larger area available to react.

It has been shown that metal nanoparticles (such as Al or Ti) cause more severe explosions than carbon-based nanomaterials and can even reach spontaneous ignition. Another important aspect is the electrical charge that high resistivity powders can accumulate, leading to spark risk and therefore, developing an ignition source.

The danger of toxicity is mainly due to the inhalation of the particles, even dermal absorption is possible but rarely. Toxicity is affected inter alia by particle shape, size and possible agglomerates. The particles enter the respiratory system and can be deposited in the alveoli or even enter the bloodstream and reach other organs such as the brain. Studies in animals have shown that genotoxic or carcinogenic effects can also be developed although there are no documented cases in humans.

Speaking specifically of nanofluids, hazards are greatly reduced since the particles are suspended in a liquid. Therefore, the danger of inhalation is minimized and the same happens with the dust explosion.

4. APPLICATION: AUTOMOTIVE RADIATOR

To check all the benefits of nanofluids seen in the bibliographic review, the program ANSYS® Engineering Simulation & 3D Design Software will be used. This program uses numerical analysis and data structures to solve and analyse problems that involve fluid flows, which is commonly known as CFD (Computational Fluid Dynamics).

The use of software for CFD simulations is the cheapest way to simulate and predict the behaviour of fluids without having to resort to the physical construction of models that besides being more expensive, require more time and, in the case of large simulations, much more space.

ANSYS® is the commercial name of the program, which in turn consists of several different modules that allow the simulation of many engineering situations. Some of these modules include fluid behaviour, mechanical strength of bodies or electromagnetic field treatment. For this project the Fluent module will be used.

Starting from a 3D model of a simplified automotive radiator, a mesh of the model will be made; and the method, the boundary conditions and other parameters will be chosen to carry out the simulation. Since the objective is to establish a comparison between a radiator with usual refrigerant fluid and one with a nanofluid as a refrigerant, two simulations will be carried out where the only variation will be the fluid circulating through the radiator.

The fluid that is commonly used to absorb the heat generated by the engine and transfer it to the atmosphere through the radiator is antifreeze/coolant. In *Figure 12*, the cooling system of a vehicle and its main parts (highlighting the path of coolant), are represented.

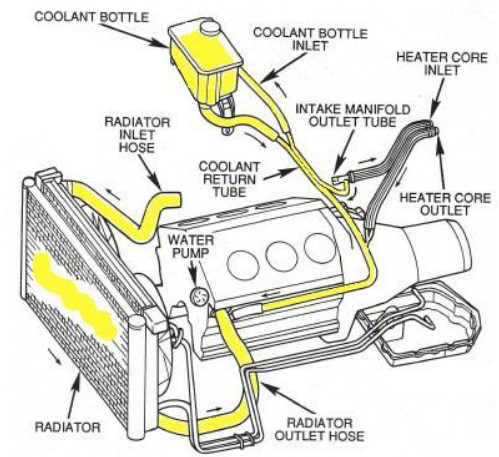

Figure 12. Cooling system of a car (via aa1car.com).

The first fluid to perform this function was water and the first modification suffered was the addition of methyl alcohol to avoid freezing. Soon, it was no longer used because its corrosion was very high, and it evaporated easily in open systems. It was not until 1959 when Adolphe Würtz, a French chemist, developed ethylene glycol. Initially this discovery did not enjoy great popularity, but this changed with the arrival of the First World War, when it began to be used as refrigerant fluid for airplanes and tanks, greatly improving the existing fluids until then. Today, antifreeze composition is as follows: 45-75% deionized / demineralized water, 25-50% ethylene glycol, 3-8% additives. The hairpin in the compositions corresponds to the different formulations of the manufacturers, which can be decanted by different proportions to prioritize more one or other properties. Additives are usually secret of each brand and include products such as defoamers, preservatives, dyes, antioxidants or corrosion inhibitors. When you see an antifreeze, what stands out most is its bright colour (green, pink and even yellow). The refrigerant itself is colourless but manufacturers add dyes so that in case of leakage it can be easily identified.

Therefore, a good antifreeze must have/be:

- Good heat capacity, to remove a lot of heat from the engine.

- High boiling temperature, higher than the maximum temperature of the engine, so it does not evaporate and continues working normally even in extreme conditions.
- Low freezing temperature, since the freezing of the liquid can lead to an increase of the volume it occupies and thus break some part of the system.
- Anti-corrosive, anti-encrusting, antifoam and low viscosity.

To carry out the simulation, next steps will be followed: geometry design, mesh generation, models set up and establishment of calculation parameters.

4.1. **GEOMETRY DESIGN**

To perform the simulation using ANSYS®, it is necessary to have a computerized model of our study. ANSYS® allows the creation of models in three dimensions from the program itself with a tool called SpaceClaim/Designmodeler or permits importing models created with other programs such as AutoCAD or SOLIDWORKS. Since the radiator model to be built will be simple, with the SpaceClaim tool it will be enough.

The created model is shown in *Figure 13* and *Figure 14* and will be used for both simulations.

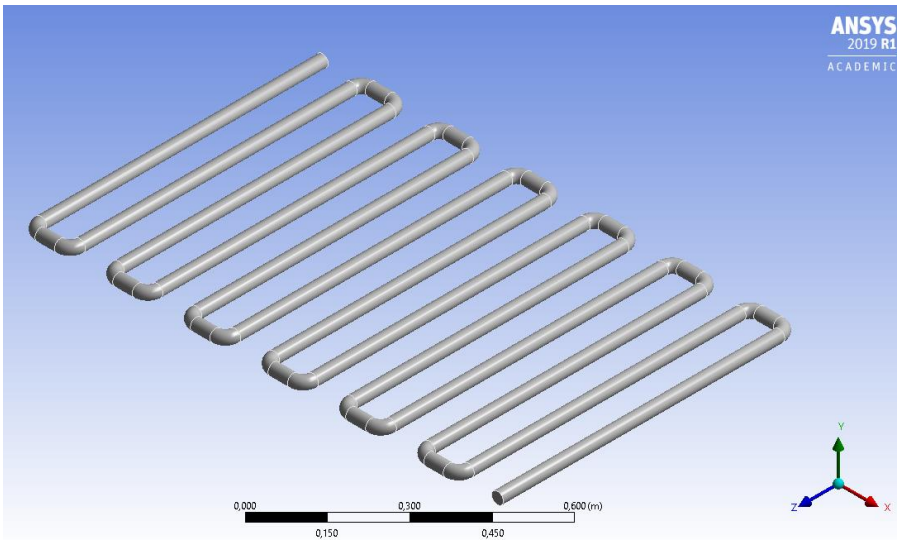

Figure 13. Radiator model used.

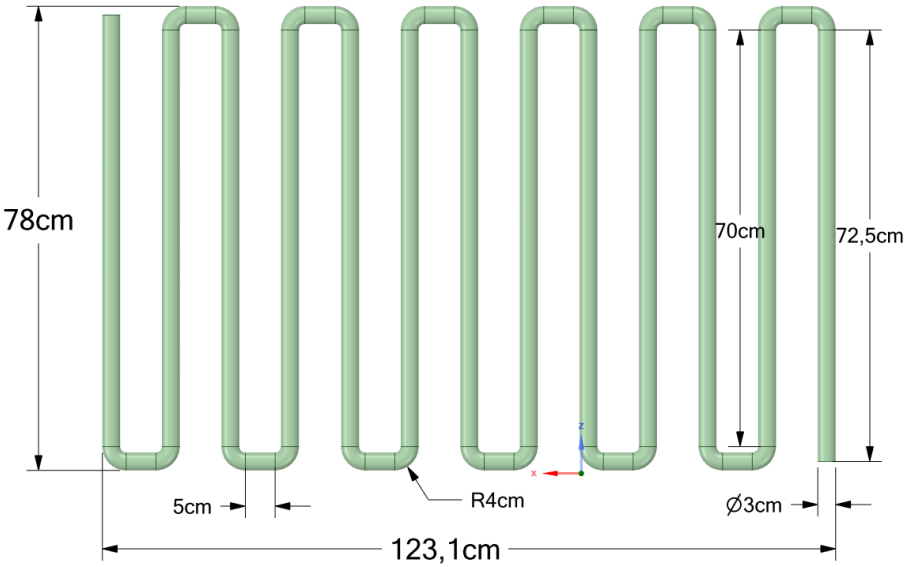

Figure 14. Radiator measurements.

The fluid runs 11.3 meters from the moment it enters until it exits at the other end.

4.2. **MESH GENERATION**

Meshing is a crucial part of the simulation, since things like the precision of the simulation, its convergence and the time required to reach a solution depend on it. If the mesh is composed of very small elements, the obtained solution will be very good, but it will be at the expense of a long computing time. Therefore, it is necessary to find a balance between precision and calculation time. In addition, it must be considered that the version of ANSYS® used (ANSYS® student version) is limited to a maximum of 512,000 elements/nodes and therefore the mesh must be adjusted to this limit. This greatly limits the possibility of making a model that approximates reality in terms of dimensions and accuracy.

The mesh used has been the same for both simulations, using triangular elements. To meet the limitations of nodes, defeature size and curvature minimum size have been adjusted to a value of $5 \cdot 10^{-3}$ m, giving a total of 444,257 elements. It is also important to name the different parts of the design so that when you reach the part of setup and establishment of the calculation parameters, everything is correctly identified, and no elements are generated with strange

names that cannot be identified or that may lead to a mistake. In the radiator mesh, three zones have been identified: inlet, outlet and all other faces as convection. Meshed model can be seen in *Figure 15*.

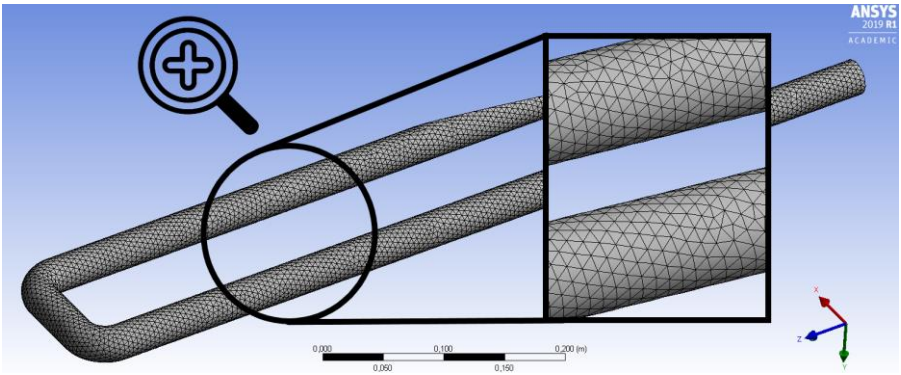

Figure 15. Radiator model meshed.

4.3. **SIMULATION SETUP**

In this step, ANSYS® Fluent module will be used. After having the meshed model, is time to define the models to solve the problem, materials, cell zone conditions, boundary conditions, resolution methods, etc.

4.3.1. ETHYLENE GLYCOL / WATER MIXTURE

Selecting models:

These are the models that have been activated; those that are not mentioned remain inactive.

- Energy: it is necessary to activate the calculation of heat transfers. ANSYS® Fluent solves the energy equation in the following form:

$$\frac{\partial}{\partial t}(\rho E) + \nabla \cdot (\vec{v}(\rho E + p)) = \nabla \cdot \left(k_{\text{eff}} \nabla T - \sum_j h_j \vec{J}_j + (\overline{\overline{\tau}}_{\text{eff}} \cdot \vec{v}) \right) + S_h \quad \textbf{(Eq. 3)}$$

- Viscous: The k-epsilon model has been used, the most common among CFD simulations, in its standard variant. The two fluids work at a Reynolds higher than 1000 and therefore it is a turbulent regime. The turbulent flow is described by means of two equations (turbulent kinetic energy [k] and dissipation [ε]).

Turbulent kinetic energy equation (k):

$$\frac{\partial(\rho k)}{\partial t} + \frac{\partial(\rho k u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_k}\frac{\partial k}{\partial x_j}\right] + 2\mu_t E_{ij}E_{ij} - \rho\varepsilon \quad \textbf{(Eq. 4)}$$

Dissipation equation (ε):

$$\frac{\partial(\rho\varepsilon)}{\partial t} + \frac{\partial(\rho\varepsilon u_i)}{\partial x_i} = \frac{\partial}{\partial x_j}\left[\frac{\mu_t}{\sigma_\varepsilon}\frac{\partial \varepsilon}{\partial x_j}\right] + C_{1\varepsilon}\frac{\varepsilon}{k}2\mu_t E_{ij}E_{ij} - C_{2\varepsilon}\rho\frac{\varepsilon^2}{k} \quad \textbf{(Eq. 5)}$$

- Also, for all flows, ANSYS® Fluent solves conservation equations for mass (or continuity equation – *Equation 6*) and momentum (*Equation 7*):

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \vec{v}) = S_m \quad \textbf{(Eq. 6)}$$

$$\frac{\partial}{\partial t}(\rho\vec{v}) + \nabla \cdot (\rho\vec{v}\vec{v}) = -\nabla p + \nabla \cdot (\bar{\bar{\tau}}) + \rho\vec{g} + \vec{F} \quad \textbf{(Eq. 7)}$$

Where stress tensor is given by:

$$\bar{\bar{\tau}} = \mu\left[(\nabla\vec{v} + \nabla\vec{v}^{\,\mathrm{T}}) - \frac{2}{3}\nabla\cdot\vec{v}I\right] \quad \textbf{(Eq. 8)}$$

Materials:

The materials chosen for the simulation were aluminium for the radiator, air for the external convection and a mixture of ethylene glycol and water as a cooling fluid. The mixture of ethylene glycol selected for the simulation is 25%, that is, it has a content in weight of monoethylene glycol of 25%. The rest (75%) is water, and additives are disregarded. Their properties, listed in

Table 2, have been obtained from bibliographic sources [24] and its values have been taken at an average temperature between the inlet and outlet of the system.

Table 2. Properties of chosen materials (1st simulation)

Material	Density [kg/m^3]	Specific Heat [J/(kg·K)]	Thermal conductivity [W/(m·K)]	Viscosity [kg/(m·s)]
Air	1.225	1,006	0.0242	$1.79 \cdot 10^{-5}$
Aluminium	2,719	871	202.4	-
Ethylene glycol-water mix	994.1	4,015	0.5329	$3.13 \cdot 10^{-4}$

Boundary conditions:

In this section it is necessary to define the conditions in which the element to be studied is. The different parts to be defined are those that have been named in the meshing section:

- Inlet: a mass flow type is chosen, with a value of 0.5 kg/s. The entry temperature is set at 385 K.
- Outlet: a pressure outlet is selected with a value of 170,000 Pa (1.7 bar). Backflow temperature is set to 323 K, even though this value doesn't affect to results.
- Convection (the rest of the faces, where there will be convection): thermal conditions are set in convection. As a coefficient of heat transfer, a value of 30 W / (m^2·K) is taken. A temperature for air of 288 K and a thickness of the radiator wall of 0.001 m are established.

Solution:

To solve the problem, SIMPLE scheme is used, selecting the second order for greater precision. Hybrid initialization is selected, and 1,500 iterations are made to ensure the convergence and stability of results.

4.3.2. ALUMINA WATER-BASED NANOFLUID

For the simulation of the radiator with the nanofluid as a refrigerant, all simulation parameters have been maintained, except for the materials section.

Materials:

For this second simulation, the following materials have been chosen: aluminum is maintained for the radiator, air is maintained as a medium for exchanging heat, and the mixture of ethylene glycol and water is exchanged for a nanofluid as cooling fluid. The chosen nanofluid has as a base fluid water and alumina nanoparticles (Al_2O_3) in a concentration of 20% (highly concentrated nanofluid). It has chosen such a high concentration to further highlight its benefits and to see greater differences in the simulations. The properties of the nanofluid have been obtained from bibliographic sources [20] and the summary of these and the rest of materials can be seen in *Table 3*.

Table 3. Properties of chosen materials (2nd simulation)

Material	Density [kg/m³]	Specific Heat [J/(kg·K)]	Thermal conductivity [W/(m·K)]	Viscosity [kg/(m·s)]
Air	1.225	1,006	0.0242	$1.79 \cdot 10^{-5}$
Aluminium	2,719	871	202.4	-
Al_2O_3 20% nanofluid	1,505	2,551	1.29	$8.96 \cdot 10^{-4}$

4.3.3. GENERAL CONSIDERATIONS

- In simulations it has been considered that the air around the radiator has no movement. This is not true because when the vehicle is in motion, radiator receives air at a certain speed. And when the car is stopped, the fan that is next to the radiator sends it air to maximize heat exchange.
- It should also be noted that the water pump that drives the fluid throughout the circuit, does not provide a constant flow as has been assumed in the simulations.

At higher engine speed, pump rotates at more rpm and therefore circulation of coolant is faster.

- There is no phase change of the refrigerant fluid in either of the two simulations.
- For the two simulations it has been decided to use the single-phase approach (introducing the properties of the fluid manually), since the results do not differ much if the multiphase model is used.

4.4. **RESULTS**

When the calculations have already been carried out and simulation is over, is time to analyze the results. In this chapter the results of the two simulations will be presented independently and a comparison between both will be established.

4.4.1. ETHYLENE GLYCOL / WATER MIXTURE

The most important variable under study in this project is temperature. The results are shown below in a contour of temperature for the 25% ethylene glycol-water mixture.

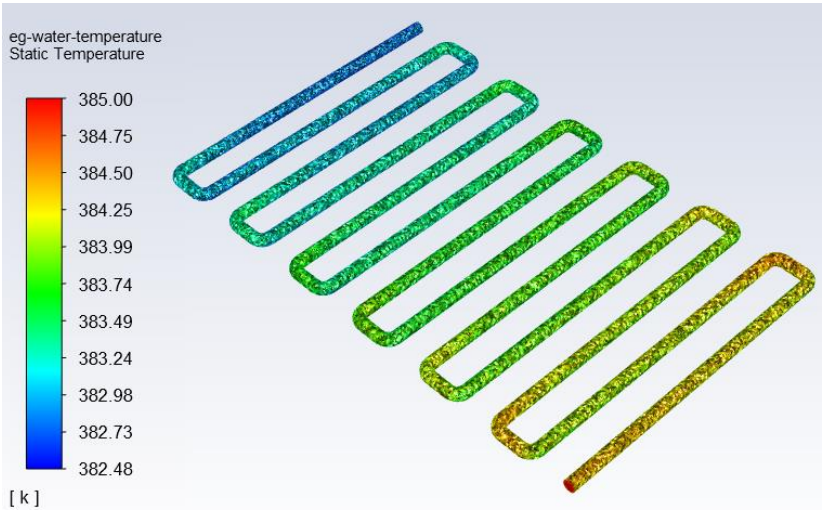

Figure 16. Temperature contour (EG - Water mix).

In addition to visual results, surface integrals tool is also used, which provides the values of a certain variable in a previously specified area or section. For this case area-weighted average will be selected. At the entrance / inlet, a value of 385 K (111.85 ºC) is obtained, as specified in program setup. At the output / outlet a value of 383.56 K (110.41 ºC) is obtained, which means a temperature difference with the input of -1.44 K.

Another important aspect to consider is the shear stress that the fluid produces in the wall of the radiator as it passes through it. As can be seen in *Figure 17*, highest stresses are in the most angular segments, while in straight parts, tension is uniform. The zones of greater tensions are also where the fluid has the highest velocity and where there is more turbulence.

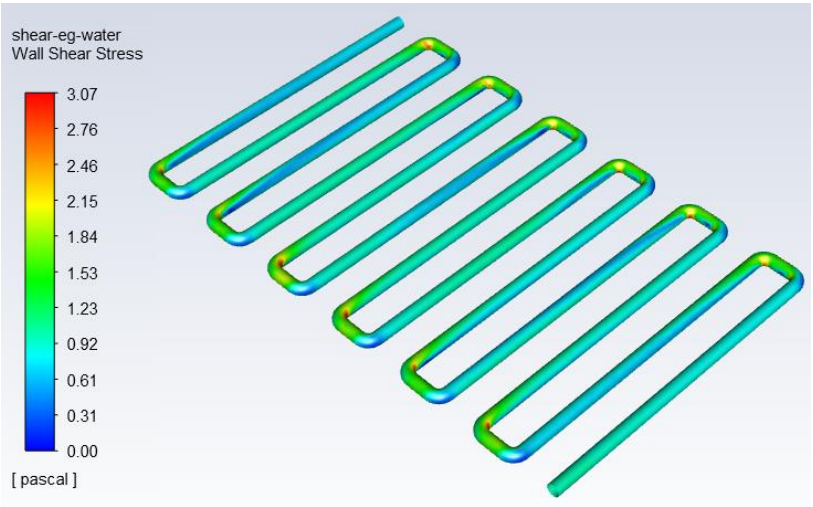

Figure 17. Wall shear stress (EG - Water mix).

Also, the pressure drop that the fluid undergoes as it passes through the radiator is important. The main reasons that cause this drop are the velocity and viscosity of the fluid, and it is important since the design of the pumping system will be commensurate with this loss. A greater pressure drop will force to install a more powerful pumping system.

As can be seen in *Figure 18*, pressure at the outlet has a value of 170,000 Pa, as specified in the setup. The simulation has led to the conclusion that the pressure at the entrance has a

value of 173,109 Pa, which means a pressure drop of the fluid as it passes through the radiator of 3,109 Pa.

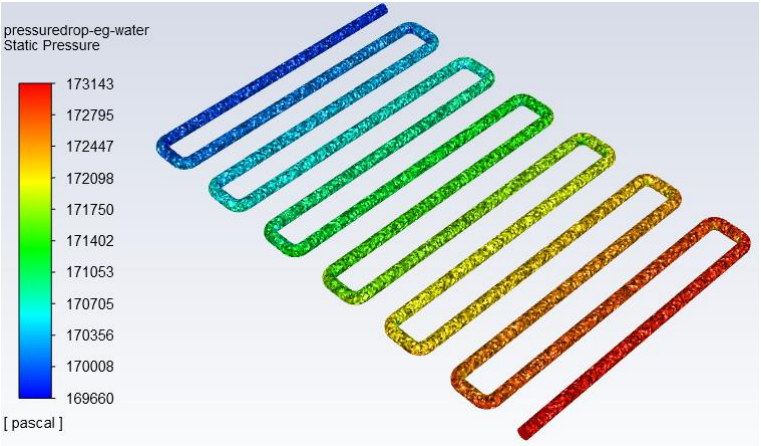

Figure 18. Pressure drop (EG - Water mix).

4.4.2. ALUMINA WATER-BASED NANOFLUID

For the simulation with nanofluid, the graph of temperature obtained is as follows:

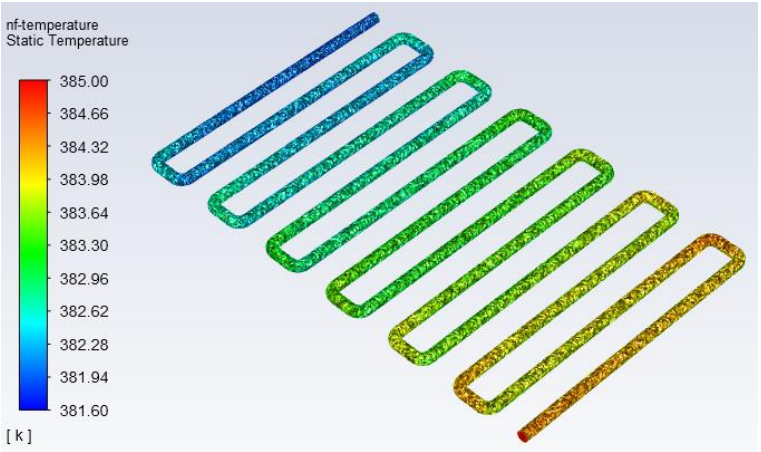

Figure 19. Temperature contour (Nanofluid).

At the inlet it has the same entry temperature as in the previous simulation: 385 K (111.85 ºC). At the outlet the fluid has a temperature of 382.81 K (109.66 °C), this means that from the moment it enters until it leaves, the fluid loses 2.19 K.

For shear stress and pressure drop, the following graphs are obtained:

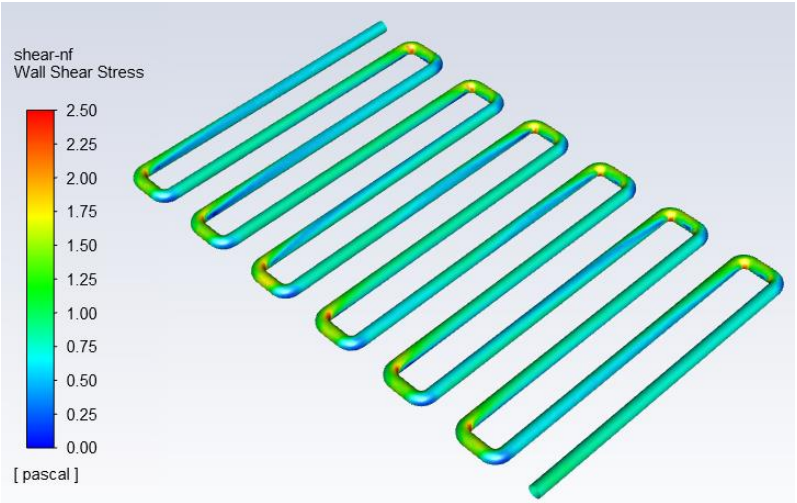

Figure 20. Wall shear stress (Nanofluid).

As mentioned before, shear stresses are higher in the elbows and lower in the straight sections.

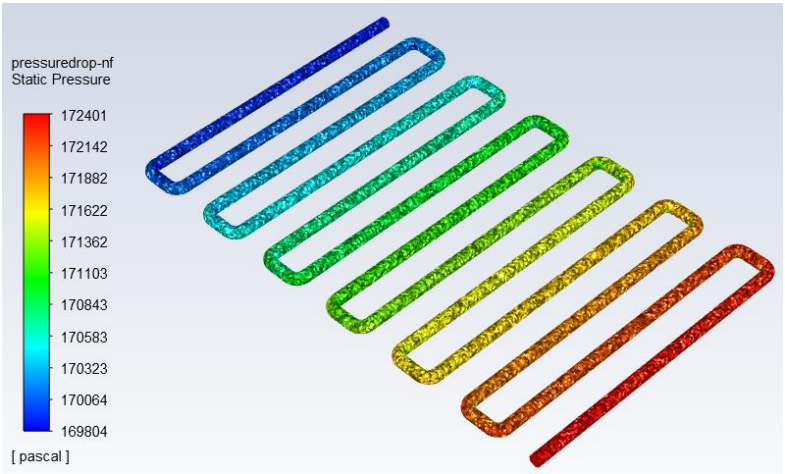

Figure 21. Pressure drop (Nanofluid).

Pressure at the output has a value of 170,000 Pa, since it has been specified in the program setup previously. At the entrance of the radiator it has a value of 172,393 Pa, which supposes a pressure drop of 2,393 Pa.

4.5. **COMPARISON**

The first thing that should be compared between the mixture of EG – Water and the nanofluid is the outlet temperature of these. Since the same temperature (385 K) has been specified at the inlet, the fluid that has a lower temperature at the outlet will be the one that has performed the most effective thermal exchange for the same radiator and conditions. The EG - Water mixture exits at a temperature of 383.56 K, while the nanofluid exits at a temperature of 382.81 K. Therefore, for the same radiator and external conditions, the use of nanofluid manages to lower the outlet temperature by 0.75 K.

At first glance it may seem a tiny improvement, but if you consider that the carried simulation is the worst-case scenario, it is a good indicator of the improvement that nanofluids can offer. It is the worst-case because, as explained above, air around the radiator does not move with a certain speed, so that it is renewed, which greatly limits heat transfer. Also, the radiator design that has been drawn for the simulation is the simplest possible. To bring it closer to reality it would be necessary to add (among other things) fins, which greatly improves transfer.

As for the shearing stress on the wall, it can be seen from the graph legend that shear stresses are superior in the EG - Water mixture. Pressure drop, that occurs when there are frictional forces (shear stress) when a fluid circulates through a pipe, are also higher in the EG - Water mixture. However, this seems to go against some characteristics of nanofluids explained in previous points of this work: when suspending particles in a base fluid, this would increase its viscosity and therefore the pressure drop would be greater. But here you can see that the nanofluid suffers a smaller pressure drop.

Shear stress depends mainly on two things: the viscosity and the velocity of the fluid through the pipe. In terms of viscosity, looking at *Tables 2 and 3*, the viscosity of the EG - Water mixture is $3.13 \cdot 10^{-4}$ kg/(m·s) while for nanofluid is $8.96 \cdot 10^{-4}$ kg/(m·s). In terms of velocity, the surface integrals tool has been used to determine the average speed of the fluids passing through the radiator. For the EG-Water mixture, a value of 0.719 m/s was found and for the

nanofluid, a value of 0.475 m/s. This difference in velocities is due to the fact that in the inlet a value of 0.5 kg/s has been specified for both simulations. When making the conversion of mass flow rate to velocity with density and surface, as the density of the nanofluid is much higher (1,505.4 kg/m^3 > 994.1 kg/m^3), it turns out that its speed is lower.

Therefore, there are two factors, and both are opposite: looking at the viscosity, the shear stress of the nanofluid should be higher; but looking at the velocity, it should be the EG - Water mix. Nevertheless, the difference in viscosity between both fluids is very small and therefore the factor that really makes the difference is the velocity. This explains why the EG - Water mixture has a higher shear stress (and also a higher pressure drop).

For the economic comparison, two refrigerants equal to those used in the simulation have been chosen. For the usual refrigerant, Krafft AR25® has been chosen. This has special protection for aluminium (material that the radiator is made of), contains 25% MEG and costs 1.89 € / L [(27)]. For the nanofluid, Al_2O_3 nanoparticles between 30 and 60 nm at 20% in water were chosen with a price of 2400 € / L [(28)]. For this particular case, the nanofluid is at a clear disadvantage in the economic aspect.

5. CONCLUSIONS

The objective of this project is to carry out a bibliographic review of the nanofluids and to try to see the possible improvement they can produce in an automotive radiator using ANSYS® Fluent. A mixture of 25% ethylene glycol in water and a nanofluid of alumina particles (20%) in water have been compared.

Analysing the results of the simulation it can be concluded that:

- What has been seen in bibliographic review has been proven: nanofluids improve conventional refrigerants due to the greater capacity of suspended particles to remove heat.
- The maximum thermal capacities are achieved with the highest concentration of nanoparticles, which leads to a greater need of pumping power compared with the same flow rate of base fluid.
- The price is the biggest obstacle that nanofluids must overcome to be commercially attractive. Although its functionality is better, if its price does not approximate current refrigerants, no one will consider its use on a large scale.
- The biggest advantage of using nanofluids is to achieve the same heat transfer using a smaller exchanger. This can be useful to develop more compact cooling systems. It does not make much sense to change a conventional fluid by a nanofluid in the same radiator since the systems of today no longer suffer from temperature.
- The stability of the nanofluid is a critical point in its preparation and use, if after being pumped along the circuit loses its stability and begins to agglomerate and sediment, its functionality will be greatly reduced.
- Although nanofluids exhibit greater thermal properties, their high price limits their use to extreme occasions where the best cooling is required regardless of cost. Today, its application to the automotive industry is not viable.

6. RECOMMENDATIONS

This section aims to be a roadmap for future research in the continuation of this project, delving into concepts that may have been touched slightly and could be interesting in-depth study.

As for the used model, it would be advisable:

- Improve the one used, in such a way that it is closer to reality. The new design should incorporate, at least, some fins to increase the exchange area. Other changes might try to approximate the geometry of the exchanger to a real one.

Regarding the simulation:

- It would be important for the air around the radiator to move at a certain speed, so that it would exchange heat and renew itself. The application of this improvement would probably be the one that would improve most the results of the simulations carried out.
- It could be interesting to study the effect of nanofluids in a physical way on cooling circuit (radiator, hoses, expansion vessel, etc.). Although nanoparticles are dispersed in a fluid, continuous beating of these against the surrounding walls could have significant effects. In the worst case, continuous abrasion of particles could lead to wear and tear of components. On the other hand, this friction could prevent accumulation of dirt that in the long term would reduce the efficiency of the cooling system.
- For greater precision, when introducing the properties of fluids, instead of taking values at an average temperature of the inlet and outlet, it would be convenient to introduce their variation model with temperature.

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ACRONYMS

CFD	Computational Fluid Dynamics
EG	Ethylene Glycol
MEG	Monoethylene Glycol
DEG	Diethylene Glycol
TEG	Triethylene Glycol
PCM	Phase Change Materials
NEPCM	Nanoenhanced Phase Change Materials
VEROS	Vacuum Evaporation onto a Running Oil Substrate
SANSS	Submerged Arc Nanoparticles Synthesis System