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Carbon Nanotube-Enhanced Nanolubricants: Stability and Performance Improvements for Automotive Use

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Abstract
Nanotechnology has been a promising technology over the years. Carbon nanotubes (CNTs) are one of the principal technologies that are developed in the nanotechnology sector. This study investigated the implementation of CNTs as additives in automotive lubricants, focusing on their impact on performance metrics. The dispersion of CNTs in lubricants is influenced by several factors, the most critical of which is the dispersion stability. Key findings include improved dispersion stability of CNTs in lubricants through adding surfactants like oleic acid, which effectively managed the aggregation issues. The CNT-enhanced lubricants exhibited superior tribological, thermophysical and rheological properties compared to the bare sample of the lubricant. Notably, the pour point was reduced from -30.5°C for the bare sample to -32°C for the treated sample, indicating enhanced low-temperature performance. Moreover, a zero cloud point value was detected too. For the viscosity test, a value around 78 mPas was obtained indicating reduction in wear and friction. Additionally, the four ball test with smoother curve showcased a better lubrication performance after applying CNTs. The noticeable improvements in the lubricant for automotive use suggested that dispersing CNT in lubricant can significantly increase the internal combustion engine efficiency. While challenges in achieving stable CNT dispersion remain, due to the easy agglomeration of nanoparticles creating non-dispersible aggregate complexes. However, the addition of surfactants presents a promising solution. Overall, CNTs demonstrated substantial potential as lubricant additive for automotive applications, exhibiting measurable enhancements in the critical performance metrics that could yield additional advantages in fuel economy and engine performance.

Keywords: Nanotechnology; Carbon nanotubes; Oleic acid; Lubricants.

1. Introduction

The efficiency of internal combustion engines in different means of transportation needs to be improved to decrease the dependence on fossil fuels and to reduce greenhouse gas emissions. To achieve this, researchers are focusing on using nanotechnology according to its special characteristics as reducing thermal and frictional losses. Consequently, Carbon nanotubes, despite their type, are being used as an additive for engine lubricants to enhance their properties and to obtain the best engine efficiency.

Engine efficiency is determined by a combination of key properties that work in concert to optimize performance. These include effective airflow management, precise timing of valves and ignition, optimal compression ratios, and efficient exhaust systems. High-quality lubricants, particularly those enhanced with nanoadditives like carbon nanotubes, play a significant role in reducing friction and wear.

However, dispersing carbon nanotubes inside lubricants faces a major problem in dispersion stability, this is due to the ease of agglomeration of nanoparticles. Dispersion stability refers to the ability of carbon nanotubes to remain uniformly distributed throughout a medium without aggregating or settling over time. One successful solution to overcome this problem is applying the colloidal theory or in other means adding a dispersing agent. These dispersing agents help in making a random motion that insists the interaction between colloidal nanoparticles. Dispersion stability for the nano-lubricant will be achieved once the repulsive forces that are found among the particles take control over the attractive forces. The dispersion stability of carbon nanotubes in lubricants remains a significant challenge due to their tendency to agglomerate. While dispersing agents have been effective in enhancing stability, recent advancements in nanoscale surface modifications, such as the use of focused ion irradiation to tune surface properties, offer promising techniques for enhancing the stability and compatibility of nanoparticles in various media. This may be applicable for improving carbon nanotube dispersion in lubricants [1]. Such methods could provide an alternative to chemical dispersants, like oleic acid, by directly modifying the CNT surface to improve dispersion and long-term stability.

The history of nanotechnology goes back to the scientist Richard Zsigmondy, he was the first to discover the meaning and importance of “Nano-meter”. He explained nanotechnology as the science and outstanding technique that uses dimensions between 1 and 100 nm in measuring particles [2]. Nanotechnology is considered the best, most common, and most interesting technology in our century. It has the power to use the methods of nanoscience in different applications, where it studies, measures & controls matter using nanometer scale. Nanotechnology is involved in almost all fields, like, chemistry, biology,

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physics, medicine and engineering. Nanotechnology, a 21st-century Fortier, was born out of such dreams. In 1925, Richard Zsigmondy was the first to discover nanometer and he was the first to measure the size of particles as gold using a microscope. Although human discovery of nanoparticles started in human history, it dramatically increased during the industrial revolution. After this, modern nanotechnology was discovered by Richard Feynman in 1965 when he introduced the concept of manipulating matter at the atomic level. Nontechnology was further advanced when a Japanese scientist named Iijma developed carbon nanotubes [3]. Beyond industrial applications, nanotechnology has also significantly impacted the biomedical field using or without artificial intelligence (AI), where nanoparticles are increasingly used as targeted drug and vaccine deliver systems. [4] [5] [6]. In addition to using them as antimicrobial potential agents [7] [8] [9] [10]. This approach, as seen in recent studies, leverages nanotechnology's precise targeting capabilities, addressing diseases more effectively and with fewer side effects than traditional methods.

As nanotechnology appears in several fields, it has shown its ability to improve and enhance many processes. One of the most important sectors is the automotive field, especially, automotive oils and lubricants. Nanomaterials are being used as an additive for conventional automotive lubricants to transfer them into a more environmentally friendly lubricant. Their several advantages like the small size and thermal stability help in enhancing the lubricants, having less wear & friction problems and also a reduction in the release of harmful emissions [11].

Carbon nanotubes (CNTs), discovered in 1991, have demonstrated significant versatility across various fields. Their applications span energy, medicine, electronics, and environmental sectors, leveraging their exceptional conductivity and absorption properties. CNTs are utilized in fuel cells, energy conservation devices, and as fillers to enhance mechanical, thermal, and electrical properties of materials, particularly in aerospace and automotive industries. Their high sensitivity makes them ideal for sensors and detectors, while their thermal conductivity improves heat dispersion in electronics. In medicine, CNTs serve as drug delivery vehicles. Environmental applications include water purification and catalysis. The aviation industry benefits from CNTs' ability to create conductive, lightweight components that protect against lightning strikes. In the automotive sector, CNTs contribute to weight reduction and improved performance in internal combustion engines, offering environmental benefits over traditional materials.

Carbon nanotubes can be simply described as graphene cylinders in the range of nanoscale that are made from rolled graphene sheets [12]. The classification of carbon nanotubes can be done according to the number of layers forming them, either, single-walled carbon nanotubes (SWCNTs), or multi-walled carbon nanotubes (MWCNTs). Single-walled carbon nanotubes are made from a single layer of graphene. In order to synthesis them, a catalyst is needed and bulk synthesis is hard. However, SWCNTs can be easily characterized, twisted, evaluated and they are more flexible. In contrast, multi-walled carbon nanotubes, consists of multiple layers of graphene. They can be prepared without the need of a catalyst and bulk synthesis is easy.

Recently, the increase in the consumption of energy and losses between elements of machines is referred to as the existence of friction and wear. To solve the problem of friction and wear between the parts of the machine, lubricants are being used in almost all means of transportation. However, the production of exceptional quality lubricant is necessary to be able to handle high temperatures and pressures among several processes [13]. Consequently, the properties of the lubricants will be enhanced and more effective by adding additives to the lubricant. So, nano-additives, or especially, carbon nanotubes, are being added to lubricants because of their extraordinary tribological and rheological properties and also because of their small size and shape [14]. Moreover, to satisfy the needs of enhancing the properties of the lubricant, specific materials, steps and procedure should be followed. For instance, preparing the lubricant itself, using a sample of carbon nanotubes with high purity level of 95% or higher to ensure best results, choosing a suitable surfactant in order to ensure that no aggregation will happen and also choosing the processing method to be used. Agglomeration refers to the tendency of individual CNTs to cluster together and form larger aggregates or bundles due to attractive forces between them.

CNT-enhanced lubricants provide significant environmental and economic benefits, including improved fuel efficiency and reduced emissions due to lower friction and wear in engines. They extend equipment life by minimizing component wear, resulting in less frequent maintenance and reduced downtime, which enhances productivity. Additionally, these lubricants often consist of non-toxic materials, contributing to environmental sustainability. The enhanced thermal management properties of CNTs lead to better heat dissipation, while their ability to reduce lubricant consumption further supports resource efficiency.

This research focuses on an in-depth study about the importance of nanotechnology in process improvement, researching the effect of carbon nanotubes in enhancing engine lubricants, decreasing fuel consumption and increasing efficiency, choosing a suitable surfactant to ensure a good dispersion stability and preventing agglomeration and finally, using the prepared carbon nanotubes and the surfactant by dispersing them in the lubricant to observe the difference in the tribological, thermophysical & rheological properties of the lubricant before and after the dispersion of CNTs.

2. Experimental

2.1 Materials

The dispersion process requires several materials and chemicals. Such as beakers, probe-sonicator, drying ovens, magnetic stirrers, heaters, balance, droppers, cloud and pour devices (WiseCircu-WCT-80), filter papers, quartz viscosimeter and 15W-50 lube oil from Mobil. The chemicals that were used are carbon nanotubes (CNTs), oleic acid (OA) as a dispersing agent and ethanol (Alpha chemical group, 96%).

2.2 Dispersing stability

The dispersion stability of carbon nanotubes in lubricants is influenced by several key factors, with dispersing agents being particularly crucial. These agents help overcome the strong van der Waals forces that promote CNT aggregation, enhancing compatibility with the lubricant medium. Other important factors include the degree of surface functionalization of CNTs, their concentration, the dispersion method employed, and the properties of the solvent or base oil used. Additionally, processing conditions like temperature and pH, as well as the viscosity of the lubricant, can impact stability. The presence of other additives may also affect CNT dispersion. Overall, effective selection and application of dispersing agents are essential for achieving stable and high-performance CNT-enhanced lubricants.

2.3 Dispersing Agent

Dispersing agents or in other means, surfactants, are critical during the dispersion process of CNTs inside lubricants. Dispersing agents, such as, Oleic Acid (OA) work by steric stabilization technique. In this technique, they seek to cover the surface of the suspended nanoparticles by creating a grafted layer around them, as shown in Fig. 1. Additionally, the presence of the elastic deformation of the grafted surface layers, produces the steric repulsive forces. When two grafted particles get close to each other, the grafted surface layer changes and thus, steric stabilization is achieved [15]. Oleic Acid was chosen for different reasons. One of these reasons is, the chemical availability. Another important reason was the ability of oleic acid to form a protective layer surrounding the nanoparticle which prevents aggregation or sedimentation.

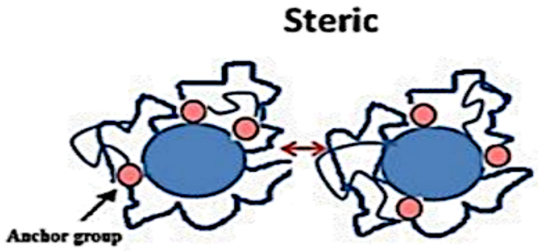

Fig. 1: Steric stabilization technique.

2.4 Dispersion Process

The preparation of the sample involved a systematic approach to achieve optimal dispersion of carbon nanotubes (CNTs) in a lubricant medium. Initially, oleic acid was incorporated at a concentration of 30%, carefully calculated based on the specific amount of carbon nanotubes utilized, alongside an appropriate volume of ethanol. The inclusion of ethanol is critical due to its polar nature, characterized by an uneven distribution of electrons that results in partial positive and negative charges. This property enhances the dispersion stability of hydrophobic carbon nanotubes within the non-polar lubricant oil, facilitating an even distribution and preventing agglomeration [16].

Ethanol functions not only as a solvent but also exhibits surfactant-like behavior, which effectively reduces the interfacial tension between CNTs and the lubricant, thus promoting better dispersion stability. The preparation process is summarized in Table 1, which outlines the specific conditions employed.

Table 1: Sample Preparation.

	Ethanol (ml)	Carbon Nanotubes (grams)	Oleic Acid (% of CNT)
Prepared sample	50	0.4	30

Following preparation, the sample was subjected to mechanical stirring at 60ºC for two hours at a speed of 300 rpm. This initial mixing phase was crucial for achieving preliminary dispersion. Subsequently, the mixture was transferred to a probe sonicator to ensure thorough homogenization, which further aids in breaking down any remaining aggregates.

After sonication, the sample was placed in a drying oven set to 70ºC for approximately 24 hours, as depicted in Fig. 2. This step is essential for removing excess solvent and ensuring that the CNTs are adequately dried.

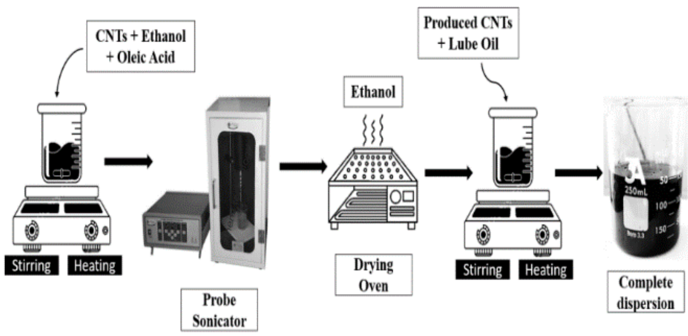

Fig. 2: Schematic diagram for the dispersion process.

Upon achieving complete dryness, the resultant carbon nanotubes were ground to obtain a fine powder, ready for subsequent dispersion into internal combustion engine lubricants. The CNT powder was then mixed with 15W-50 engine oil using a stirrer at 60ºC for four hours at a speed of 1000 rpm, ensuring a uniform and homogenous mixture suitable for application in lubrication systems.

This detailed process highlights the importance of each step in achieving effective dispersion and stability of carbon nanotubes within lubricant formulations, ultimately enhancing their performance characteristics.

3. Results and Discussion

3.1 The Thermophysical Properties

Thermophysical properties are the physical characteristics that relate the material's behavior and response to the changes in temperatures and thermal status. These properties include tests like pour point and cloud point. The pour point of an engine oil represents the lowest temperature at which the oil will still have the ability to pour or flow when temperatures are cooled down under specific conditions. However, the cloud point is known as the temperature at which solid components and wax crystals starts to form and thus oil becomes cloudy.

The prepared sample (CNT-treated sample) containing carbon nanotubes with a 30% dispersing agent, provided a value of pour point equal to -32ºC as shown in Fig. 3 compared to a value of -30.5ºC for the bare sample (untreated sample). This value shows the excellent and effective performance of the lubricant during very cold weather, due to having better dispersion stability in the lube oil. On the other hand, at extremely low temperatures, the prepared sample (CNT-treated sample) detected no cloud point as shown in Fig. 4 compared to a value of 13ºC for the bare sample (untreated sample). This means that at these low-temperature conditions of the engine oil, the oil will still flow easily, and no clouds or waxes will be formed and no clogging occurs.

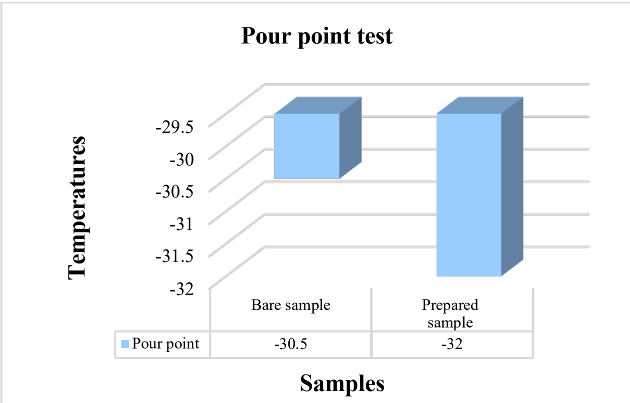

Fig. 3: Pour point results.

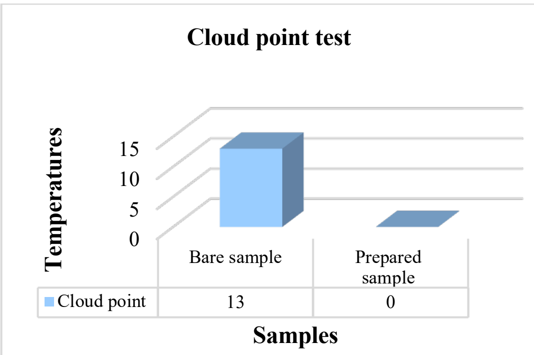

Fig. 4: Cloud point results.

Dispersing carbon nanotubes inside the lubricants can be very effective in decreasing both the pour and cloud point of the lubricant and thus leaving the lubricant more fluid at very low temperature. This is because CNTs act as pour point depressants by disrupting wax crystal formation in the oil, which typically increases viscosity and pour point in cold conditions. This results in improved cold-start performance and better low-temperature operability for lubricants.

3.2 Rheological Properties

The rheological characteristics are known as the flow and deformation behavior of different materials under conditions of either stress, strain, or both. The rheological properties are necessary during studying the performance of lubricants because they determine the behavior of the lubricant after being exposed to several conditions like, temperature, shear rate and pressure. Viscosity is considered to be an important factor in these properties.

The lubricant's resistance to the flow is known by the measurement of the viscosity. Viscosity provides information about the ability of the lubricants to form a protective film between the moving parts, reducing wear and friction as well as improving the efficiency and performance of different equipment and engines.

The highest viscosity was detected to be 150 mPas in the bare oil sample (untreated sample) at 25ºC. However, the sample mixed with carbon nanotubes (CNT-treated sample) showed fewer values of viscosity, which was equal to 78 mPas at 29ºC as shown in Fig. 5. Nanotechnology has transformed numerous industries due to its unique properties at the nanoscale, enhancing fields from automotive lubricants to biomedical research. For instance, surface acoustic streaming techniques in microfluidic systems have been employed to generate multicellular tumor spheroids rapidly, advancing cancer research by enabling realistic in vitro tumor models [17]. Similarly, in the automotive sector, carbon nanotubes (CNTs) serve as innovative additives in lubricants, enhancing properties such as thermal stability and reducing wear. This study focuses on CNT dispersion in automotive lubricants, aiming to improve fuel efficiency and engine performance by minimizing internal friction and thermal losses.

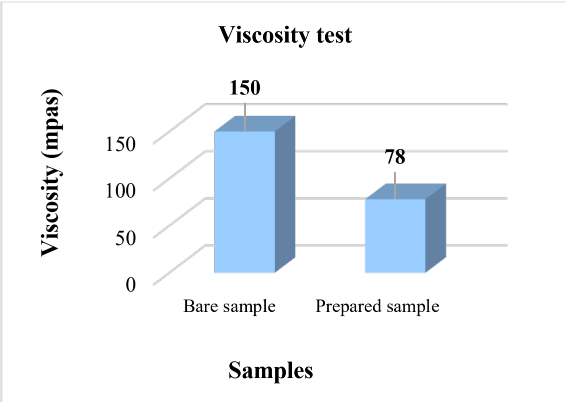

Fig. 5: Viscosity results.

Carbon nanotubes have different properties that make them able to enhance the viscosity by decreasing it, such as, high aspect ratio, high surface area and excellent thermal and mechanical properties. The addition of carbon nanotubes to the lubricants can help in making changes to the internal structure of the lubricant, which helps in decreasing the viscosity. In other means, decreasing lubricant's resistance to flow.

3.3 Tribological Properties

Tribological properties are known by the characteristics of materials that have an effect on their performance in friction and wear interactions. Friction refers to the resistance of motion when two surfaces slide in opposite to each other. Four ball test is considered an important test to be done in this section. The coefficient of performance was tested for both bare lube oil sample and the sample containing carbon nanotubes. It was obvious that this sample showed better lubrication performance unlike the bare lube oil sample as it started with a very rough curve, the starting point or the initial spike, due to the static force. The lower the coefficient of friction, the better the performance and thus, reduction in wear on engine components as shown in Fig. 6.

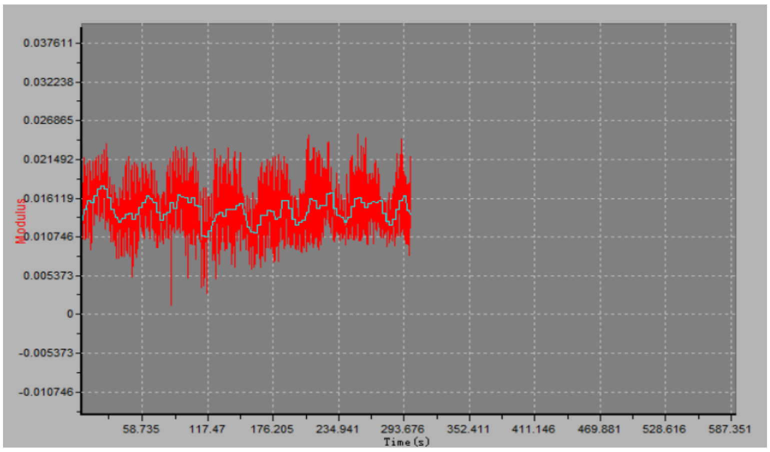

Fig. 6: Four ball test results of the sample containing CNTs.

When carbon nanotubes were dispersed in the engine oil, their additives slowly seep into the contact interface along with the oil, depositing on the pits and grooves to form a protective film between the surfaces of the engine's parts. This helps in increasing the thickness of oil film, producing smooth surfaces between parts of the engine, decreasing the formation of sharp particles, as well as having less friction as a result of the additive lubrication action

4. Conclusion

This research focused on the power of nanotechnology in our time. Nanotechnology falls within many different fields and applications this is because nanotechnology has the ability to produce lighter, stronger, and more efficient materials and equipment which will positively impact many industries. In this study, carbon nanotubes were dispersed in the 15W-50 engine oil. Additionally, the prepared sample (CNT-treated sample) was tested to record the performance and enhancement of the lube oil after dispersing carbon nanotubes inside it. During the thermophysical tests, it was obvious that when the pour point of the lube oil is too high, oil becomes too thick to pour and flow easily which negatively affects the system. This means that the pour point is very necessary to be noticed to select the most suitable lubricant to be used during different operations. Dispersing carbon nanotubes inside the lubricants can be very effective in decreasing the pour point of the lubricant and thus leaving the lubricant more fluid at very low temperatures. This is because carbon nanotubes can behave as pour point depressants, as they can interfere with wax crystal formation in the lube oil, which are responsible for the increase in viscosity and the increase in pour point at low temperatures. Moreover, during the cloud point test, when temperatures become too low in lubricants and cloud point is reached, filters begin to clog, and the flow of the oil will be restricted, which will result in decreasing the lubrication performance and negatively affect the components of the internal combustion engine.

For the rheological test and specially, the viscosity test, it was noticed that the increase in the viscosity of the lubricants leads to more resistance in the lubricant's ability to flow. Thus, lubrication becomes more difficult between the equipment and engine parts. When viscosity is increased, friction and power consumption are increased too due to the need for more energy to overcome the fluid's internal resistance. However, when viscosity is decreased the lubricant becomes more fluid and easier to distribute through the parts of the internal combustion engine. Additionally, lower viscosity helps in minimizing friction and power consumption. This reduction in the values of the viscosity will lead to emissions reduction such as, reducing carbon dioxide (CO_2) as well as fuel consumption. Moreover, lower viscosity means faster engine warm-up times, enhancing the efficiency of cold start and overall thermal efficiency improvement through the system. This proved that, the addition of carbon nanotubes helped in decreasing the viscosity at higher temperatures. This meats the specifications of modern lubricants, specifically, in engines, in order to ensure that the lube oil has the ability to flow easily through the components of the internal combustion engine under high conditions [18].

For tribological tests such as four ball test, was done for determining the friction of the lube oil before and after the dispersion. This test proofed the improvement in the friction of the lubricant sample containing carbon nanotubes with high concentration of oleic acid compared with the bare lubricant sample as it provided a protective layer between the parts of the engine and thus reduced friction.

The real-world implementation of carbon nanotubes in engine lubricants faces several challenges. One major issue is maintaining dispersion stability, as CNTs tend to agglomerate, which can diminish their effectiveness. Additionally, optimizing the concentration of CNTs is critical; too low may not yield significant benefits, while too high can increase viscosity and risk clogging. Compatibility with existing lubricant additives must also be ensured to avoid interference with their functions. Long-term effects on engine components require thorough investigation to prevent adverse impacts. Cost considerations and scalability of high-quality CNT production are significant hurdles, along with potential environmental and health concerns related to their use. Furthermore, establishing industry standards for quality control and obtaining regulatory approvals adds complexity to the implementation process. Addressing these challenges is essential for successfully integrating CNT-enhanced lubricants into commercial applications.

Conflicts of interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper. This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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