Chapter 6

Summary and Conclusions

Recent trends in nano-additives for engine oil (EO) and lubricating oil applications focus on enhancing the performance and efficiency of these oils through the incorporation of nanoparticles. Researchers are exploring a variety of nanoparticles, such as metal oxides, carbon-based materials, and hybrid composites, due to their unique properties at the nanoscale. These nano-additives significantly improve the rheological properties of oils by reducing friction and wear, leading to smoother and more efficient engine operation. Additionally, they enhance the thermal conductivity of lubricating oils, allowing for better heat dissipation and improved temperature regulation in mechanical systems. The overall result is extended engine life, reduced energy consumption, and lower maintenance costs, making nano-additives a promising advancement in the field of lubrication technology. Therefore, nano-additives are of specific interest in the field of lubricating oils' additives and are used to form nanofluids for targeted rheology and thermal conductivity requirements.

Castor (CO) has been long utilized commercially as a highly renewable resource in the chemical industry. India has been recognized as the world leader in castor seed and oil production, dominating the international CO trade. The unique structure of CO imparted properties that made it suitable for various industrial applications. In lubricating applications, CO was valued for its high viscosity, excellent lubricity, and ability to perform well under extreme temperatures. Similarly, in the commercial market, EO, also known as motor oil or lubricating oil, was essential for the efficient and long-lasting operation of internal combustion engines. Its primary functions included lubricating moving parts to reduce friction and wear, dissipating heat generated during engine operation, and preventing damage to engine components. In the Indian market, 10W30T grade EO is crucial because of its ability to provide optimal performance in variable temperature range, ensuring reliable engine protection and efficiency. This grade is particularly important for the diverse climate conditions across India, offering excellent lubrication and reducing engine wear in both hot and cold environments. The versatile physico-chemical characteristics of nano-additives established them as important ingredients in lubricating oil formulations. The nano-additives used in the current research at different concentrations in various base oils, specifically CO and EO, are shown in Table 6.1.

Table 6.1: Types of the CO and EO based nanofluids containing different nano-additives studied in the present work.

Nano-additives	CO based nanofluid	EO based nanofluid
Alumina (Al_2O_3)	Al_2O_3/CO	Al_2O_3/EO
Zinc Oxide (ZnO)	ZnO/CO	ZnO/EO
Graphene nanoplatelets (GNP)	GNP/CO	GNP/EO
Multiwalled carbon nanotubes (MWCNT)	MWCNT/CO	MWCNT/EO

In the present research work, the physico-chemical evaluation of two different base oils like CO and EO has been investigated. For nano-additive development, hydrothermal method was employed to synthesize metal-oxide based nano-additives. The developed metal-oxide and carbon-based nano-additives were analysed for the structural and chemical composition by sophisticated characterization techniques, such as SEM, XRD, and EDX. These developed nano-additives were further used with chosen base oil for flow and thermal conductivity improvement study. The nanofluid development process involved the probe sonication method, ensuring the effective dispersion of nano-additives in the base oils. Rigorous evaluation of the synthesized nanofluids was conducted through rheological analysis using a rheometer and thermal conductivity analysis using a thermal conductivity meter. The present thesis work is comprised in to six chapters.

Chapter 1: General introduction

In this chapter introduction, initial research aspects and the importance of oils have been discussed. The current scenario and classification of the oils based on their chemical structure & American Petroleum Institute (API) standards have been shown with the latest research citations. The CO and EO oils have been discussed in order to gain a better understanding of their applications in various lubricating fields.

The significance and advancements in the research of nano-additives, a new class of oil additives were highlighted. The synthesis, types, lubrication mechanisms, and current research progress on nano-additives are discussed. The development and advantages of nano-additives for lubricating oils and nanofluid synthesis have been furnished.

The influence of nano-additives on the rheology and thermal conductivity of base oils and their nanofluids is explained with detailed mechanisms.

This chapter provides an up-to-date introduction to the present research work, focusing on CO, EO, and nano-additive blended nanofluids for lubrication applications.

Chapter 2: Materials and methods

Chapter 2 covers the extraction of CO, its specifications, procurement, and the initial physico-chemical evaluation of its basic properties. These properties include appearance, specific gravity, hydroxyl number, saponification value, iodine number, acid value, kinematic viscosity, and viscosity index. Similarly, detailed information is provided for studied EO.

The chapter also details the various methods and techniques used in the present work for the characterization of nano-additives and nanofluids. The characterization of nano-additives through XRD, SEM, and EDS is discussed with a theoretical background. In-depth details are provided for the instruments used for rheology and thermal conductivity measurements of base oil and nanofluids. Specifications and applications of the instruments and equipment used to synthesize nano-additives and nanofluids, such as the hydrothermal reactor, probe sonicator, balance, pH meter, and ovens, are also covered in this chapter.

Chapter 3: Nano-additives for development of Castor Oil and Engine Oil- based Nanofluids

In this Chapter-3, to improve the flow and thermal conductivity properties of the base oils like CO and EO, various nano-additives (a) alumina (Al_2O_3), (b) zinc oxide (ZnO), (c) graphene nanoplatelets (GNP), and (d) multiwalled carbon nanotubes (MWCNT) were developed and systematically characterized.

The metal-oxide based nano-additives [alumina (Al_2O_3) and zinc oxide (ZnO)] were synthesized hydrothermally and their systematic characterization using various techniques such as XRD, SEM, and EDX have been shown. Fig. 6.1 indicates the complete process of nano-additives and nanofluids development. Similarly, two important commercially procured carbon-based nano-additives: GNP and MWCNT were also characterised for their potential use in the creation of nanofluids.

In EDX analysis, no characteristic peaks of any impurities were detected, suggesting that high quality of Al_2O_3, ZnO, GNP, and MWCNT nanoparticles was prepared. While crystallite size calculated from the XRD pattern using the Scherrer's equation for all nano-additives which indicate less than 100nm crystallite size. Table 6.2 indicates type of crystal system and calculated crystallite size of all individual developed nano-additives.

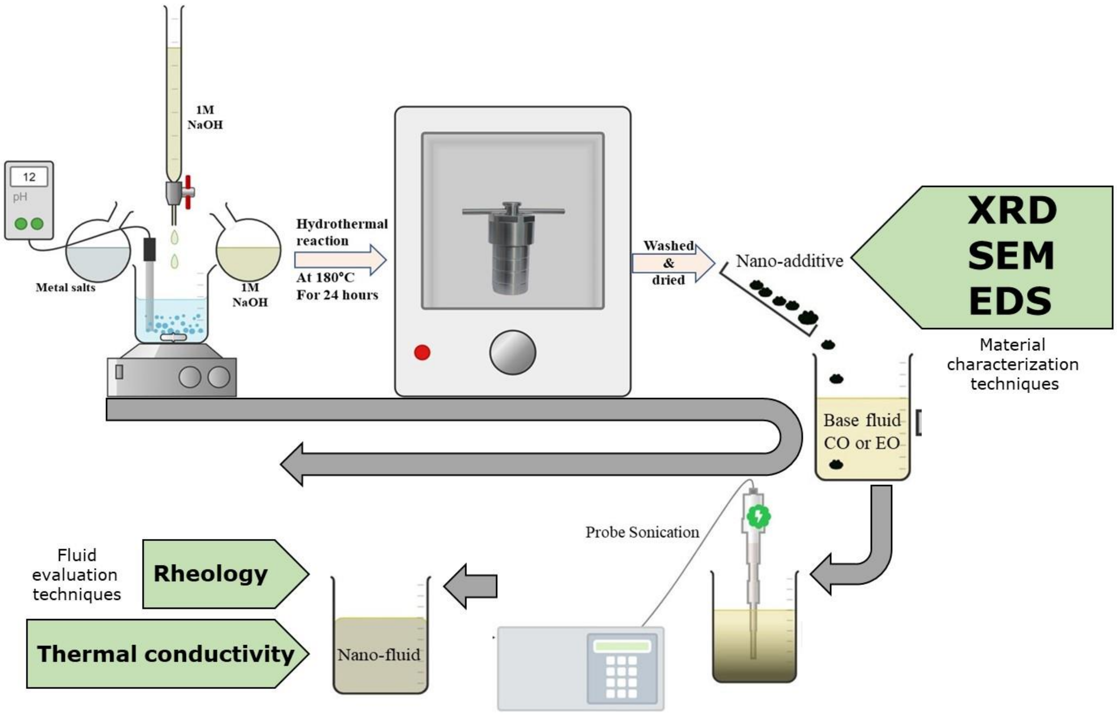

Fig. 6.1: Graphical presentation of synthesis of nano-additives and nanofluids with characterization techniques used.

Table 6.2: The crystal system parameters of developed nano-additives.

Nano-additive	Crystal system	Crystallite size (nm)
Al_2O_3 nanoparticles	Rhombo hydral	69.59
ZnO nanoparticles	Hexagonal	44.31
Graphene nanoplatelets (GNP)	Hexagonal	19.59
Multiwalled carbon nanotubes (MWCNT)	Hexagonal	9.92

The current study demonstrated a hydrothermal method for synthesizing different nanoparticles and its characterization techniques. Thus, development of nano-additives may represent an effective approach for enhancing flow and thermal conductivity properties of base oils i.e., CO and EO for lubricating applications.

Chapter 4: Castor oil-based nanofluids containing Al_2O_3, ZnO, GNP and MWCNT nano-additives

In the Chapter-4, the rheological and thermal conductivity properties of extracted CO are modified using the developed Al_2O_3, ZnO, GNP and MWCNT nano-additives, which has impact on flow and thermal behaviour of base oil. The CO-based nanofluid were prepared by adding developed nano-additives powder into pure CO by a double step procedure as shown in Fig. 6.1. Homogeneous CO-based nanofluids were obtained by using a high-power ultra-sonication probe having a 500-watt output power and a 20 kHz frequency power supply. Following CO-based nanofluids prepared by dispersing nano-additives:

1. CO-based nanofluids containing Al_2O_3 nano-additives (Al_2O_3/CO nanofluids),
2. CO-based nanofluids containing ZnO nano-additives (ZnO/CO nanofluids),
3. CO-based nanofluids containing GNP nano-additives (GNP/CO nanofluids), and
4. CO-based nanofluids containing MWCNT nano-additives (MWCNT/CO nanofluids)

A comprehensive rheological investigation was conducted to evaluate the dynamic viscosity of both pure CO and all prepared CO-based nanofluids. Prepared CO-based nanofluids consist different nano-additives at variable concentrations (here, weight% of 0.05, 0.1, 0.2, and 0.5 %), shear rates (here, 0 to 5000 s^{-1}), and temperatures (here, 40ºC, 60ºC, 80ºC, and 100ºC) conditions. Rheological investigation revealed that all the CO and CO-based nanofluids exhibits Newtonian fluid flow behaviour except CO-ZnO nanofluid of 0.2 and 0.5 weight % at 60ºC. The power law index (n) values for 0.5 weight % GNP/CO nanofluids, obtained at 60°C, 80°C and 100°C temperature ranges, are close to or equal to one. This observation confirms the Newtonian flow behaviour of GNP/CO nanofluids. The power law index (n) values for 0.2 weight % Al_2O_3/CO and MWCNT/CO nanofluids, obtained at 60°C, 80°C and 100°C temperature ranges, are close to or equal to one that confirms the Newtonian flow behaviour of Al_2O_3/CO and MWCNT/CO nanofluids. ZnO/CO nanofluids shows instability in flow behaviour as nano-additive concentration and temperature changes. Fig. 6.2 depicts the fluid flow characteristics of all developed CO-based nanofluids at different temperatures concluded from rheological investigation.

Developed nanofluids with different nano-additive concentrations	***Temperature (°C)*** ***40***	***60***	***80***	***100***
Pure-CO	PP	N	N	D
Al_2O_3/CO (0.05%)	PP	N	N	D
Al_2O_3/CO (0.1%)	PP	N	N	N
Al_2O_3/CO (0.2%)	PP	N	N	N
Al_2O_3/CO (0.5%)	PP	N	N	PP
ZnO/CO (0.05%)	PP	N	N	D
ZnO/CO (0.1%)	PP	N	N	D
ZnO/CO (0.2%)	PP	PP	N	N
ZnO/CO (0.5%)	PP	PP	N	N
GNP/CO (0.05%)	PP	N	N	D
GNP/CO (0.1%)	PP	N	N	D
GNP/CO (0.2%)	PP	N	N	D
GNP/CO (0.5%)	PP	N	N	N
MWCNT/CO (0.05%)	PP	N	N	D
MWCNT/CO (0.1%)	PP	N	N	D
MWCNT/CO (0.2%)	PP	N	N	N
MWCNT/CO (0.5%)	PP	N	N	PP

Fluid behavior type	**PP: Pseudo plastic non-Newtonian**	**N: Newtonian**	**D: Dilatant non-Newtonian**

Fig. 6.2: Schematic representation of various developed CO-based nanofluids flow behaviour at different temperatures.

Thermal conductivity on all developed nano-additive dispersed CO-based nanofluids revealed that carbon-based nano-additives (GNP and MWCNT) increases thermal conductivity of base fluid greater than the metal-oxide based nano-additives (Al_2O_3 and ZnO). GNP nano-additive shows maximum thermal conductivity enhancement of 23% at 0.5 weight % concentration at 70°C. GNP and MWCNT at 0.5 weight % nano-additives concentration, increases thermal conductivity of base CO fluid by more than 10% for all temperature range measured. GNP and MWCNT exhibit higher thermal conductivity compared to metal-oxide nano-additives due to their unique structural and material properties. In contrast, metal-oxide nano-additives (Al_2O_3 and ZnO) typically have poor thermal conductivity due to their crystalline structures and the presence of lattice defects, grain boundaries, and phonon scattering sites.

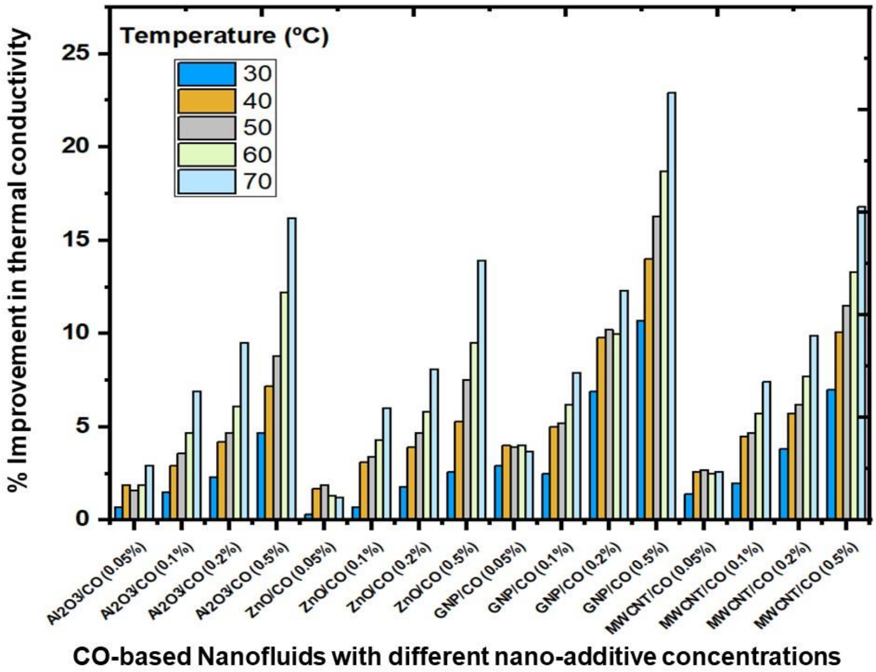

Fig. 6.3: Schematic representation of various developed CO-based nanofluids thermal conductivity improvement at different temperatures.

Overall, the rheological and thermal conductivity studies indicated, for consistent lubrication in engine components applications where Newtonian fluid with high thermal conductivity is desirable, 0.5 weight % GNP/CO nanofluid is suitable nanofluid. For high-pressure and temperature environments within engines, 0.5 weight % Al_2O_3/CO and MWCNT/CO are found suitable pseudoplastic nanofluids with approximate 17% thermal conductivity improvement as compared to CO base fluid. Carbon based nano-additives are the "smart nano-additives" that offer a new stratagem for efficient lubricating oil characteristics with better thermal and flow properties, and could be utilized for various lubrication applications for optimum efficiency.

Chapter 5: EO-based nanofluids containing Al_2O_3, ZnO, GNP and MWCNT nano-additives

In the Chapter-5, the rheological and thermal conductivity properties of procured synthetic grade (10W-30) EO by are modified using the developed Al_2O_3, ZnO, GNP and MWCNT nano-additives, which has impact on flow and thermal behaviour of EO base oil as discussed in chapter-4. Similarly, the EO-based nanofluid were prepared by adding developed nano-additives powder into pure EO by a double step procedure as shown in Fig. 6.1.

Following EO-based nanofluids prepared by dispersing nano-additives.

1. EO-based nanofluids containing Al_2O_3 nano-additives (Al_2O_3/EO nanofluids),
2. EO-based nanofluids containing ZnO nano-additives (ZnO/EO nanofluids),
3. EO-based nanofluids containing GNP nano-additives (GNP/EO nanofluids), and
4. EO-based nanofluids containing MWCNT nano-additives (MWCNT/EO nanofluids)

Developed nanofluids with different nano-additive concentrations	Temperature (°C) 40	60	80	100
Pure-EO	N	PP	PP	PP
Al_2O_3/EO (0.05%)	N	PP	PP	PP
Al_2O_3/EO (0.1%)	N	N	PP	PP
Al_2O_3/EO (0.2%)	N	N	PP	PP
Al_2O_3/EO (0.5%)	N	N	PP	PP
ZnO/EO (0.05%)	N	PP	PP	PP
ZnO/EO (0.1%)	N	N	PP	PP
ZnO/EO (0.2%)	N	N	PP	PP
ZnO/EO (0.5%)	N	N	PP	PP
GNP/EO (0.05%)	N	PP	PP	PP
GNP/EO (0.1%)	N	N	PP	PP
GNP/EO (0.2%)	N	N	N	PP
GNP/EO (0.5%)	N	N	N	PP
MWCNT/EO (0.05%)	N	N	PP	PP
MWCNT/EO (0.1%)	N	PP	PP	PP
MWCNT/EO (0.2%)	N	PP	PP	PP
MWCNT/EO (0.5%)	N	PP	PP	PP

Fluid behavior type	PP: Pseudo plastic non-Newtonian	N: Newtonian	D: Dilatant non-Newtonian

Fig. 6.4: Schematic representation of various developed EO-based nanofluids flow behaviour at different temperatures.

A comprehensive rheological investigation was conducted to evaluate the dynamic viscosity of both pure EO and all prepared EO-based nanofluids. Prepared EO-based nanofluids consist different nano-additives at variable concentrations (here, weight% of 0.05, 0.1, 0.2, and 0.5 %), shear rates (here, 0 to 5000 s^{-1}), and temperatures (here, 40ºC, 60ºC, 80ºC, and 100ºC) conditions. Rheological investigation revealed that all the EO and EO-based nanofluids exhibits Newtonian fluid flow behaviour for all concentrations at 40ºC. At 100°C temperature, EO and EO-based nanofluids exhibits pseudo plastic non-Newtonian fluid flow behaviour for all concentrations. While, at 60°C and 80°C temperatures, all EO-based nano-fluids showed different flow behaviour based on nano-additives nature and concentrations. Fig. 6.4 depicts the fluid flow characteristics of all developed EO-based nanofluids at different temperatures concluded from rheological investigation.

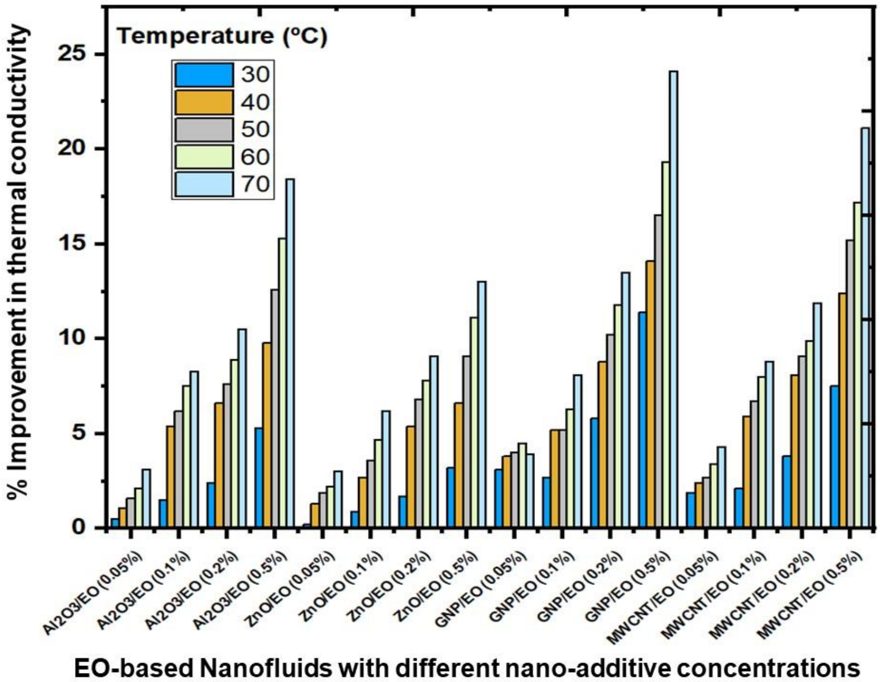

Fig. 6.5: Schematic representation of various developed EO-based nanofluids thermal conductivity improvement at different temperatures.

Thermal conductivity on all developed nano-additive dispersed EO-based nanofluids revealed that carbon-based nano-additives (GNP and MWCNT) increases thermal conductivity of base fluid greater than the metal-oxide based nano-additives (Al_2O_3 and ZnO). GNP nano-additive shows maximum thermal conductivity enhancement of 24% at 0.5 weight % concentration at 70°C. GNP and MWCNT at 0.5 weight % nano-additives concentration, increases thermal conductivity of base EO fluid by more than 10% for all temperature range measured. GNP and MWCNT exhibit higher thermal conductivity compared to metal-oxide nano-additives due to their unique structural and material properties. In contrast, metal-oxide nano-additives (Al_2O_3 and ZnO) typically have poor conductivity due to their crystalline structures and the presence of lattice defects, grain boundaries, and phonon scattering sites.

Overall, the rheological and thermal conductivity studies indicated, for consistent lubrication in engine components applications where Newtonian fluid with high thermal conductivity is desirable, 0.5 weight % GNP/EO nanofluid is suitable nanofluid. For high-pressure and temperature environments within engines, 0.5 weight % MWCNT/EO was found suitable pseudoplastic nanofluids with approximate 21% thermal conductivity improvement as compared to EO base fluid. Carbon based nano-additives are the "smart nano-additives" that offer a new stratagem for efficient lubricating oil characteristics with better thermal and flow properties, and could be utilized for various lubrication applications for optimum efficiency.

In conclusion, the results of our investigation clearly indicate that due to advantage of superior thermal conductivity i.e., because of highly ordered atomic structures of GNP and strong covalent bonding between carbon atoms, GNP nano-additive dispersed GNP/CO and GNP/EO nanofluids hold substantial promise as valuable and cost-effective materials for diverse lubrication and heat transfer applications in automotive industry.