DETECTION OF HYDROCARBON LEVEL IN DISTILLED WATER USING LASER INDUCED ACOUSTIC TECHNIQUE

RAHELEH HOSSEINIAN SARBALAEI

UNIVERSITI TEKNOLOGI MALAYSIA

DETECTION OF HYDROCARBON LEVEL IN DISTILLED WATER USING LASER INDUCED ACOUSTIC TECHNIQUE

RAHELEH HOSSEINIAN SARBALAEI

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Physics)

Faculty of Science
Universiti Teknologi Malaysia

JUNE 2015

To:

My parents and my beloved family

تقدیم به پدر بزرگوار و مادر مهربانم

آن دو فرشته ای که از خواسته هایشان گذشتند، سختی ها را به جان خریدند و خود را سپر بلای مشکلات و ناملایمات کردند، تا من به جایگاهی که اکنون در آن ایستاده ام برسم.

تقدیم به :

پدرم به استواری کوه

مادرم به زلالی چشمه

برادرانم به صمیمیت باران

خواهرانم به طراوت شبنم

ACKNOWLEDGEMENT

I would like to express my special appreciation and thanks to my supervisor Professor Dr. Noriah Bt Bidin, she has been a tremendous mentor for me. I would like to thank her for encouraging my research and for allowing me to grow as a research scientist. Her advice on both research as well as on my career have been invaluable.

I would also like to thank my Co-supervisor, Dr. Jasman bin Zainal, who has also provided insightful discussions about the research. I am also very grateful for his scientific advice and knowledge and many insightful discussions and suggestions.

My thanks are also due to the staff, faculty members, and technicians of the Faculty of Science, Universiti Teknologi Malaysia, who contributed to my research.

I also thank Dr. Waskito Nugroho, for his helpful advice and co-operating while he was a postdoc in the Laser-physics Laboratory.

I especially thank my family. My hard-working parents have sacrificed their lives for us and provided unconditional love and care. I love them so much, and I would not have made it this far without them. I know I always have my family to count on when times are rough.

I truly thank Dr. Safaa, for all his advice, help and support during my study and Special thanks to Maryam for all her support during writing my thesis.

Last but not the least, I would like to thank my friends (too many to list here but you know who you are!) and all my colleagues for providing support and friendship that I needed.

ABSTRACT

Oil spill occurs almost every day. Department of chemistry Malaysia (JKM) took almost a week or more days to analyze it. Therefore alternative technique should be considered. In this work, a new technique is introduced by using laser technology and piezoelectric transducer. The system is known as Laser Induced Acoustic (LIA). Lube oil was used as a hydrocarbon sample. Distilled water and hydrochloric acid were employed for solution preparation with different concentrations in the range of 0 - 1000 ppm. Hydrocarbon became impurities in the solution, which can be observed via CCD video camera after illumination by diode pumped solid-state laser (DPSS). Refractive index of hydrocarbon solution was measured by He-Ne laser following Snell's law. A Q-switched Nd:YAG laser was focused to induce optical breakdown and shock wave generation. This phenomenon was recorded via high-speed photography system. Dye laser pumped by nitrogen laser was employed as a source of flashlight. Digital delay generator was deployed to synchronize both lasers. CDD camera was interfaced with personnel computer with Matrox version 9 software, which was used to record shock wave. Silicone photodiodes were employed to detect both lasers. Optical delay between two lights represented the frozen time of shock wave generation. The time delay was manifested via digital oscilloscope. Shock wave propagation in hydrocarbon solution was also detected via piezoelectric transducer. The sound signal was also displayed on the same oscilloscope. The sound amplitude (volt) was calibrated via hydrometer to estimate shock wave pressure (atm). Shadowgraph image of shock wave was analyzed via ImageJ software. Shock wave radius was measured and divided by optical delay to determine sound speed in hydrocarbon solution at different concentration. Observation result showed that sound speed linearly increases with hydrocarbon concentrations. Similarly sound amplitude was found linearly increasing with hydrocarbon concentrations. This is due to a lot of mass transfer which gives rise to high impact to the transducer. Combination of high-speed photography and transducer detection validate the shock wave as the mechanism to determine the hydrocarbon concentration. Hence sound speed is the fingerprint for every hydrocarbon solution. Furthermore sound speed has linear relationship with hydrocarbon concentration. Similarly the sound amplitude has linear relationship with hydrocarbon concentration. This similarity indicates that the hydrocarbon concentration can be detected based on sound generation via laser induced acoustic technique.

ABSTRAK

Tumpahan minyak berlaku hampir setiap hari. Jabatan Kimia Malaysia (JKM) mengambil masa hampir seminggu atau lebih untuk menganalisisnya. Oleh itu, teknik alternatif perlu dipertimbangkan. Satu teknik baru diperkenalkan dengan menggunakan teknologi laser dan transduser piezoelektrik. Sistem ini dikenali sebagai akustik beraruh laser (LIA). Minyak pelincir telah digunakan sebagai sampel hidrokarbon. Air suling dan asid hidroklorik digunakan untuk menyediakan larutan dengan kepekatan dalam julat 0 ke 1000 ppm. Hidrokarbon menjadi benda-asing dalam larutan dan dapat diperhatikan melalui kamera video CCD yang disinari dengan laser keadaan pepejal berpamkan diod. Indeks biasan larutan hidrokarbon diukur dengan menggunakan Laser He-Ne dan mengikut hukum Snell. Laser Nd:YAG bersuis-Q difokuskan untuk membentuk runtuhan optik dan menjana rambatan gelombang kejutan. Fenomena ini dirakamkan dengan sistem fotografi kelajuan tinggi. Laser pencelup yang dipam oleh laser nitrogen digunakan sebagai lampu kilat. Penjana tundaan masa digital digunakan untuk menyerentakan kedua-dua laser tersebut. Kamera video CCD yang dihubungkan dengan komputer peribadi melalui perisian MATROX versi 9 telah digunakan untuk merakamkan gelombang kejutan. Fotodiode silikon digunakan untuk mengesan kedua-dua laser. Tundaan masa optik antara kedua-dua cahaya ini mewakili masa pembekuan rambatan gelombang kejutan. Masa tundaan ini dipaparkan pada osiloskop digital. Gelombang kejutan dalam larutan hidrokarbon juga dikesan melalui transduser piezoelektrik. Isyarat bunyi ini dipaparkan dalam osiloskop digital yang sama. Amplitud bunyi (volt) telah dikalibrasi menggunakan hidrometer untuk menganggarkan tekanan gelombang kejutan (atm). Imej geraf bayangan gelombang kejutan dianalisis menggunakan perisian ImageJ. Jejari gelombang kejutan diukur dan dibahagikan dengan masa tundaan optik untuk menentukan halaju bunyi dalam larutan hidrokarbon pada kepekatan yang berbeza. Hasil pemerhatian menunjukkan halaju bunyi bertambah dengan kepekatan hidrokarban. Begitu juga amplitud bunyi bertambah dengan kepekatan hidrokarbon. Ini disebabkan oleh pemindahan jisim yang banyak memberi impak yang tinggi pada transduser. Gabungan sistem fotografi kelajuan tinggi dan pengesanan transduser mengesahkan bahawa gelombang kejutan adalah mekanisma penentu kepekatan hidrokarbon. Oleh itu halaju bunyi menjadi cap jari bagi setiap larutan hidrokarbon. Tambahan pula halaju bunyi mempunyai hubungan linear dengan kepekatan hidrokarbon. Begitu juga amplitud bunyi mempunyai hubungan linear dengan kepekatan hidrokarbon. Penyamaan ini menunjukkan bahawa kepekatan hidrokarbon boleh dikesan berdasarkan bunyi yang dijanakan melalui teknik akustik aruhan laser (LIA).

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

AP	-	Amplified Photodiode
API	-	American Petroleum Institute
CCl4	-	Carbon Tetrachloride
CCD	-	Charge-Coupled Device
CFC	-	Chlorofluorocarbon
DOP	-	Delayed-Output Pulse
DPSS	-	Diode Pumped Solid-State
DDG	-	Digital Delay Generator
EB	-	Expanded Beam
GCMS	-	Gas Chromatography Mass Spectrometer
He-Ne	-	Helium-Neon
HCL	-	Hydrochloric Acid
JKM	-	Jabatan Kimia Malaysia
LIA	-	Laser Induced Acoustic
LLPG	-	Liquid-Liquid Partition-Gravimetric
NIR	-	Near Infrared
Nd: YAG	-	Neodymium-Doped Yttrium Aluminum Garnet
NDT	-	Nondestructive Testing
ND	-	Nitro-Dye
OT		Opthothermal
Osc	-	Oscilloscope
ppm	-	Parts Per Million
PA	-	Photoacoustic
PD	-	Photo Detector

PZT	-	Piezoelectric Transducer
SNR	-	Signal To Noise Ratio
FTIR	-	Transform Infrared Spectrometry
UV	-	Ultra Violet

LIST OF SYMBOLS

(atm)	-	Atmosphere
a.u	-	arbitrary unit
cm	-	Centimeter
°C	-	Centigrade
gr	-	Gram
Hz	-	Hertz
J	-	Jules
MHz	-	Mega hertz
m	-	Meter
ml	-	Milliliter
µl	-	Microliter
ms	-	Millisecond
mm	-	Millimeter
ns	-	Nanosecond
µs	-	Microsecond
mJ	-	Milli jules
nm	-	Nanometer
Pa	-	Pascal
ppm	-	Part per million
s		Second
V	-	Voltage
W	-	Watt
λ	-	Wavelength

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Overview

Oil poses a range of environmental risks and causes wide public concern when released into the environment, whether as catastrophic spills or chronic discharges [1]. An oil spill is the release of liquid petroleum hydrocarbon into the environment, especially marine areas, due to human activity, and is a form of pollution. Oil spills may be due to releases of crude oil from tankers, offshore platforms, drilling rigs and wells, as well as spills of refined petroleum products (such as gasoline and diesel) and their by-products, heavier fuels used by large ships such as bunker fuel, or the spillage of any oil refuse or waste oil [2]. Cleanup and recovery from an oil spill is difficult and depends upon many factors, including the type of oil spilled, the temperature of the water (affecting evaporation and biodegradation), and the types of shorelines and beaches involved. Spills may take weeks, months or even years to clean up. Therefore, to unambiguously characterize, identify, categorize, and quantify all sources of hydrocarbons entering the environment is important. It is crucial for the environmental damage assessment; the evaluations of the relative risks to the ecosystem posed by each spill, and for selecting the appropriate spill response and taking effective cleanup measures.

The usual method uses the liquid–liquid separation technique to determine quantitatively the amount of oil dispersed at sea [3-7]; However the separation technique has certain constraints, including being time consuming, only being performed in a laboratory, and using hazardous chemicals such as N-hexane and Freon, which are carcinogens. The recent Fourier transform technique too has the same constraints [8]. That is why scientists seek a fast and easy in situ technique to determine amounts of oil spilled at sea. The high power laser is one of the best candidates to be used to solve this problem. A Q-switched laser is able to induce an acoustic shock wave, which has high potential for transient detection techniques. Nanosecond- pulsed breakdown in a liquid phase has wide application in many other fields [9-14].

The Laser-Induced Acoustic (LIA) is a very sensitive technique to apply for a wide range of applications. Laser Induced Acoustic is part of a family of optothermal techniques (OT), which are based on the conversion of optical into mechanical energy. Especially for the solid and liquid media, the generating and detecting of acoustic waves accrued using a short pulse laser-based technique. This technique was demonstrated as an important tool and used for many applications such as in the medical areas and applied sciences. Furthermore, this technique can be used for material characterization [15, 16], surface cleaning from the contaminations [17], laser tissue ablation, corneal sculpting [18] and indirect gall stone fragmentation [19]. The rapid heating, thermoelastic expansion, and phase change occur during the interaction between the laser and surface of solid media, while the interaction between the laser and liquid media, emission of a strong ultrasonic or shock wave would occur [20, 21].

1.2 Problem Statement

Pollution and its control are very important and effecting issues on human life. One of the crucial materials to be controlled from being polluted in human life is water. Thus one of the factors among many pollutant factors is hydrocarbon in water.

In Jabatan Kimia Malaysia (JKM), at Bahagian Alam Sekitar, a large number of samples from various organization either government or private sectors received daily for analysis. JKM provides the chemical analysis services (Appendix A) from liquid to solid form in different conditions. The analysis is divided in two parts; control analysis and enforcement analysis.

For the controlling part, they analyze the specific parameters in order to confirm that the samples are obliging with acts and regulations as stated in Act 127 “Environmental Quality Acts and Regulations”. They perform this analysis monthly for the monitoring purposes. While for the enforcement analysis, the samples undergo specific tests in order to determine specific parameters depending on the needs. The samples can be sewage, discharged water from factory, and fire debris. The samples of seawater received by JKM, is to determine the level of Hydrocarbon. The chemical techniques known as liquid-liquid Partition-Gravimetric (LLPG) techniques, Gas Chromatography Mass Spectrometer (GCMS), and Fourier Transform Infrared Spectrometry (FTIR) are used.

In LLPG technique, liquid samples such as seawater and river water undergo the digestions process. Usually, the purpose of this technique is to separate the hydrocarbons from water. The digestion process takes approximately 24-36 hours. Finally, the concentration can be measured by using mass technique as follow:

$$\text{Concentration} = (\text{Final mass} - \text{initial mass}) / \text{volume} \tag{1.1}$$

In this technique, the used solvent such as, carbon tetrachloride ($CCl4$), and chlorofluorocarbon (CFC) are harmful to the environment according to the well-documented ozone layer depletion. Then, the GCMS is used to determine the type of hydrocarbons by separating the chemical bonding in accordance to the mass percentage; however, GCMS requires the sample in gas form. Then, the technique namely, FTIR spectrometer is being used to determine the type of sample either water or oil. The disadvantages of the aforementioned technique in addition to the harmfully for the environment; it is also a time consuming technique and labor intensive. Therefore, other alternative technique needs to be considered to reduce the processing time as well as the chemical application. Therefore LIA was proposed in order to reduce the limitations of chemical method.

1.3 Research Objectives

This main objective of this research is to develop a new method namely Laser Induced Acoustic (LIA) technique to determine the hydrocarbon level in water. In attempts to achieve this goal the following tasks are established:

1. To observe and characterize the shock wave properties in different hydrocarbon concentration
2. To detect the acoustic signal in different hydrocarbon concentration
3. To correlate between the acoustic properties and the concentration of the hydrocarbon.

1.4 Scope of the study

In this study, Lube oil was used as hydrocarbon sample. Distilled water was used as solution instead of seawater, because hydrocarbon is assumed to be as contamination in water. The hydrocarbon concentration was studied in the range of 0-1000 ppm. A Q-switched Nd:YAG laser was deployed to induce optical breakdown associated with acoustic shock wave generation. Dye laser pumped by nitrogen laser was used as a flash of light to illuminate the shock wave propagation. A digital delay generator was used as a synchronizer unit. High-speed photography technique was used to grab high-speed phenomena. CCD video camera was used to record the acoustic shock wave via Matrox version 9 software. He-Ne laser was used to measure refractive index following the Snell's law. Diode pumped solid-state laser (DPSS) were utilized to characterize the hydrocarbon solution properties. Piezoelectric transducer was employed to detect the present of acoustic signal. Digital oscilloscope was used to display the acoustic signal as well as the optical delay. Hydrometer was used to calibrate the transducer.

1.5 Significant of the study

A new technique that is laser induced acoustic shock wave was introduced to detect the level of hydrocarbon in water. The level of hydrocarbon is expected to be determined based on the knowledge either the speed of sound of the pressure of the acoustic signal. The proposed technique has a potential to be used for detecting the hydrocarbon level in water based on a green technology. It is faster, clean and environmentally friendly.

1.6 Thesis outline

This thesis is consisting of five chapters. Chapter 1 provides an overview on the hydrocarbon detection using current conventional methods such as physical and chemical methods and the necessity of new method for hydrocarbon detection in water. The research problem statement, objectives, scope and significance of this study are described in this chapter. The literature review of previous research of oil detection and techniques of detections are described in details in Chapter 2. This chapter tries to highlight a relationship between the hydrocarbon detection and laser induced acoustic. Chapter 3 presents in detail the methodology of sample preparation, system characterizations, calibration and data analysis. The method used for signal detection, high-speed photography system is explained in this chapter. Chapter 4 shows the results and discussions. This is also includes the shockwave captured by high-speed photography system and acoustic signal detection, hydrocarbon impurities in water and optical properties of media. Chapter 5 concludes the significant findings and further recommendations on this diversified research possibility. The limitations related with our investigation are highlighted.

REFERENCES

1. Bohy, M., Dridi, L., Schäfer, G. and Razakarisoa, O. Transport of a mixture of chlorinated solvent vapors in the vadose zone of a sandy aquifer. Vadose Zone Journal. 2006. 5(2): 539-553.
2. Pezeshki, S., Hester, M., Lin, Q. and Nyman, J. The effects of oil spill and clean-up on dominant US Gulf coast marsh macrophytes: a review. Environmental Pollution. 2000. 108(2): 129-139.
3. Houck, M. M. and Siegel, J. A. Separation Methods: Fundamentals of Forensic Science 2nd edn (Amsterdam:Elsevier) 2010: p 123.
4. David, W., Letcher, T. M., Ramjugernath, D. and David Raal, J. Activity coefficients of hydrocarbon solutes at infinite dilution in the ionic liquid, 1-methyl-3-octyl-imidazolium chloride from gas–liquid chromatography. The Journal of Chemical Thermodynamics. 2003. 35(8): 1335-1341.
5. Kenny, D. V. and Olesik, S. V. Extraction of lignite coal fly ash for polynuclear aromatic hydrocarbons: modified and unmodified supercritical fluid extraction, enhanced-fluidity solvents, and accelerated solvent extraction. Journal of chromatographic science. 1998. 36(2): 59-65.
6. Horacio J , S. P. a. M. G. A. Technol.Pet.Sci. 1998. 16: 377.
7. Palamarev, C. E., Kandinska, M. I. and Palamavera, M. D. Automatic Selection of Mobile Phases. IV. Thin- Layer Chromatography on Silica of Simple and Complex Organic Compounds. Journal of Liquid Chromatography & Related Technologies. 2004. 27(13): 2003-2018.
8. Nyakas, A., Han, J., Peru, K. M., Headley, J. V. and Borchers, C. H. Comprehensive Analysis of Oil Sands Processed Water by Direct-Infusion Fourier-Transform Ion Cyclotron Resonance Mass Spectrometry with and without Offline UHPLC Sample Prefractionation. Environmental science & technology. 2013. 47(9): 4471-4479.
9. Alwafi, Y., Bidin, N., Gustiono, D. and Harun, S. Alloying aluminum with

Fe using laser induced plasma technique. Laser Physics. 2012. 22(8): 1364-1367.

10. Cao, Y., Wang, Z., Li, G., Wu, Y. and Zhou, J. Experimental study on scale removal from special-shaped conduits through underwater electrical discharge. Proceedings of the Journal of Physics: Conference Series: IOP Publishing. 012127.

11. Desarkar, H., Kumbhakar, P. and Mitra, A. One-step synthesis of Zn/ZnO hollow nanoparticles by the laser ablation in liquid technique. Laser Physics Letters. 2013. 10(5): 055903.

12. Khalil, A. Spectroscopic studies of UV lead plasmas produced by single and double-pulse laser excitation. Laser Physics. 2013. 23(1): 015701.

13. Lautz, J., Sankin, G. and Zhong, P. Turbulent water coupling in shock wave lithotripsy. Physics in medicine and biology. 2013. 58(3): 735.

14. Seepersad, Y., Pekker, M., Shneider, M. N., Dobrynin, D. and Fridman, A. On the electrostrictive mechanism of nanosecond-pulsed breakdown in liquid phase. Journal of Physics D: Applied Physics. 2013. 46(16): 162001.

15. Chirtoc, M. Thermal Wave Physics and Related Photothermal Techniques: Basic Principles and Recent Development, edited by E. Marin, Transworld Research Network. 2009.

16. Wang, L. V. Photoacoustic imaging and spectroscopy: CRC press. 2009.

17. Schmid, T. Photoacoustic spectroscopy for process analysis. Analytical and bioanalytical chemistry. 2006. 384(5): 1071-1086.

18. Pushkarsky, M., Webber, M., Baghdassarian, O., Narasimhan, L. and Patel, C. K. N. Laser-based photoacoustic ammonia sensors for industrial applications. Applied Physics B. 2002. 75(2-3): 391-396.

19. Wang, C. and Sahay, P. Breath analysis using laser spectroscopic techniques: Breath biomarkers, spectral fingerprints, and detection limits. Sensors. 2009. 9(10): 8230-8262.

20. Meyer, P. and Sigrist, M. Atmospheric pollution monitoring using CO2-laser photoacoustic spectroscopy and other techniques. Review of scientific instruments. 1990. 61(7): 1779-1807.

21. Miklós, A., Hess, P. and Bozóki, Z. Application of acoustic resonators in photoacoustic trace gas analysis and metrology. Review of scientific instruments. 2001. 72(4): 1937-1955.

22. Cheremisinoff, N. P. Handbook of water and wastewater treatment technologies: Butterworth-Heinemann. 2001.
23. Baah, B. Phytoremediation of Hydrocarbon Contaminated Soil-A Case Study at Newmont Ghana Gold Limited–Ahafo Kenyasi. 2011.
24. Al, P., Grasshoff, K., Thorell, L. and Tsiban, A. Assessment of the effect of pollution on the natural resources of the baltic sea, 1980. 1981.
25. Fingas, M. The basics of oil spill cleanup: CRC Press. 2012.
26. McIntyre, A., Baker, J., Southward, A., Bourne, W., Hawkins, S. and Gray, J. Oil Pollution and Fisheries [and Discussion]. Philosophical Transactions of the Royal Society of London. B, Biological Sciences. 1982. 297(1087): 401-411.
27. Paine, R. T., Ruesink, J. L., Sun, A., Soulanille, E. L., Wonham, M. J., Harley, C. D., Brumbaugh, D. R. and Secord, D. L. Trouble on oiled waters: lessons from the Exxon Valdez oil spill. Annual Review of Ecology and Systematics. 1996: 197-235.
28. Holba, C. Exxon Valdez Oil Spill. EVOS Trustee Council Librarian: Alaska resource library & information services. 2014. 1-17.
29. Manglallan, E. P. Water Quality Baseline Study and Non-Point Source Pollution Analysis on Waikele Stream, West Loch Estuary, Oahu, Hawaii. DTIC Document. 1994.
30. Butts, K. H., Bradshaw Jr, A. L. and Smith, B. D. The Role of the Military in Protecting the World's Water Resources: Proceedings 3-5 November 1999. DTIC Document. 2000.
31. Hooker, S. K. and Gerber, L. R. Marine reserves as a tool for ecosystem-based management: the potential importance of megafauna. BioScience. 2004. 54(1): 27-39.
32. Boesch, D. F., Butler, J. N., Cacchione, D. A., Geraci, J. R., Neff, J., Ray, J. P. and Teal, J. M. An assessment of the long-term environmental effects of US offshore oil and gas development activities: future research needs. Long Term Environmental Effects of Offshore Oil and Gas Development. 1987.
33. Oshima, K., Kajiyama, J. and Fukumoto, S. Method and material for separating oil from oil-containing water. US Patent 3,617,566. 1971.
34. O'Connell, E., O'Keeffe, S., Newe, T. and Lewis, E. Low cost hydrocarbon spillage sensor for the marine environment with interfacing to a mote

platform. Proceedings of the Sensors, 2011 IEEE: IEEE. 1558-1561.

35. Reeves, G. Understanding and monitoring hydrocarbons in water. Oakville, Ontario, Canada: Arjay Engineering LTD. 2005.

36. Magoon, L. B. and Dow, W. G. The petroleum system. The petroleum system—From source to trap: AAPG Memoir. 1994. 60: 3-24.

37. Cerniglia, C. E. and Heitkamp, M. A. Microbial degradation of polycyclic aromatic hydrocarbons (PAH) in the aquatic environment. Metabolism of polycyclic aromatic hydrocarbons in the aquatic environment. CRC Press, Inc., Boca Raton, Fla. 1989: 41-68.

38. Veil, J. A., Puder, M. G., Elcock, D. and Redweik Jr, R. J. A white paper describing produced water from production of crude oil, natural gas, and coal bed methane. prepared by Argonne National Laboratory for the US Department of Energy, National Energy Technology Laboratory, January. Available at http://www. ead. anl. gov/pub/dsp_detail. cfm. 2004.

39. Maples, R. E. Petroleum refinery process economics: PennWell Books. 2000.

40. Stengel, D., O'Reilly, S. and O'Halloran, J. Contaminants and pollutants. The Ecology of Transportation: Managing Mobility for the Environment: Springer. 361-389; 2006.

41. Speight, J. G. The chemistry and technology of petroleum: CRC press. 2014.

42. Kjersem, A. B. Proteome changes in Atlantic cod (Gadus morhua) exposed to oil and produced water: discovery of biomarker candidates for environmental monitoring. 2007.

43. Cole, G. M. Assessment and remediation of petroleum contaminated sites: CRC Press. 1994.

44. Olah, G. A. and Molnar, A. Hydrocarbon chemistry: John Wiley & Sons. 2003.

45. McCain, W. D. The properties of petroleum fluids: PennWell Books. 1990.

46. Schwarzenbach, R. P., Gschwend, P. M. and Imboden, D. M. Environmental organic chemistry: John Wiley & Sons. 2005.

47. Speight, J. G. Petroleum Refining and Environmental Control and Environmental Effects. Fossil Energy: Springer. 61-97; 2013.

48. Balba, M., Al-Awadhi, N. and Al-Daher, R. Bioremediation of oil-contaminated soil: microbiological methods for feasibility assessment and field evaluation. Journal of microbiological methods. 1998. 32(2): 155-164.

49. Kvenvolden, K. A. Organic geochemistry–A retrospective of its first 70 years. Organic geochemistry. 2006. 37(1): 1-11.

50. Braun, R. L. and Burnham, A. K. Chemical reaction model for oil and gas generation from type I and type II kerogen. Office of Scientific and Technical Information PO Box. 1993. 62.

51. Ltd., S. I. The Petroleum Handbook, 6th ed. ed. New York: Elsevier Science. 1986.

52. Balba, M., Al-Daher, R., Al-Awadhi, N., Chino, H. and Tsuji, H. Bioremediation of oil-contaminated desert soil: the Kuwaiti experience. Environment International. 1998. 24(1): 163-173.

53. Collins, C. D. Implementing phytoremediation of petroleum hydrocarbons. Phytoremediation: Springer. 99-108; 2007.

54. Irwin, R. J. Environmental contaminants encyclopedia. 1998.

55. Villalobos, M., Avila-Forcada, A. P. and Gutierrez-Ruiz, M. E. An improved gravimetric method to determine total petroleum hydrocarbons in contaminated soils. Water, air, and soil pollution. 2008. 194(1-4): 151-161.

56. Potter, T. L. Analysis of petroleum contaminated soil and water: An overview. Principles and practices for petroleum contaminated soils. 1989: 97-109.

57. Salanitro, J. P., Dorn, P. B., Huesemann, M. H., Moore, K. O., Rhodes, I. A., Rice Jackson, L. M., Vipond, T. E., Western, M. M. and Wisniewski, H. L. Crude oil hydrocarbon bioremediation and soil ecotoxicity assessment. Environmental Science & Technology. 1997. 31(6): 1769-1776.

58. Gibbs, J. and Kennebunk, M. Selecting the detection system—colorimetric, fluorescent, luminescent methods. Corning Life Sciences ELISA Technical Bulletin. 2001. 14.

59. Stuart, B. Infrared spectroscopy: Wiley Online Library. 2005.

60. Valeur, B. and Berberan-Santos, M. N. Molecular fluorescence: principles and applications: John Wiley & Sons. 2012.

61. Tielens, A. G. Interstellar polycyclic aromatic hydrocarbon molecules*. Annu. Rev. Astron. Astrophys. 2008. 46: 289-337.

62. Festou, M. and Atreya, S. Voyager ultraviolet stellar occultation measurements of the composition and thermal profiles of the Saturnian upper atmosphere. Geophysical Research Letters. 1982. 9(10): 1147-1150.

63. Maesen, T., Botman, M., Slaghek, T., She, L.-Q., Zhang, J. and Ponec, V. On platinum catalysts of hydrocarbon reactions and the possible role of Pt ions. Applied Catalysis. 1986. 25(1): 35-41.
64. Vlug, A., Nieuwenhuys, E. J., van Eijk, R. V., Geertzen, H. G. and van Houte, A. J. Nephelometric measurements of human IgG subclasses and their reference ranges. Annales de biologie clinique. 1994. 52(7-8): 561-567.
65. Mendes-Bezerra, A. and Uden, P. A nephelometric method for the determination of sulphate in the presence of barium by using chloroaminobiphenyl: application to organic compounds and hydrocarbon oils. Analyst. 1969. 94(1117): 308-312.
66. Jäger, J. Detection and characterization of nitro derivatives of some polyclic aromatic hydrocarbons by fluorescence quenching after thin-layer chromatography: application to air pollution analysis. Journal of Chromatography A. 1978. 152(2): 575-578.
67. Lin, E. L., Cormier, S. M. and Torsella, J. A. Fish biliary polycyclic aromatic hydrocarbon metabolites estimated by fixed-wavelength fluorescence: comparison with HPLC-fluorescent detection. Ecotoxicology and environmental safety. 1996. 35(1): 16-23.
68. Fernández-Sánchez, J., Carretero, A. S., Cruces-Blanco, C. and Fernández-Gutiérrez, A. Highly sensitive and selective fluorescence optosensor to detect and quantify benzo [a] pyrene in water samples. Analytica chimica acta. 2004. 506(1): 1-7.
69. Murphy, B. and Mcloughlin, P. Determination of Chlorinated hydrocarbon species in aqueous solution using Teflon coated ATR Waveguide/FTIR spectroscopy. International Journal of Environmental & Analytical Chemistry. 2003. 83(7-8): 653-662.
70. Oberhüttinger, C., Langmeier, A., Oberpriller, H., Kessler, M., Goebel, J. and Müller, G. Hydrocarbon detection using laser ion mobility spectrometry. International Journal for Ion Mobility Spectrometry. 2009. 12(1): 23-32.
71. Falate, R., Kamikawachi, R., Müller, M., Kalinowski, H. and Fabris, J. Fiber optic sensors for hydrocarbon detection. Sensors and Actuators B: Chemical. 2005. 105(2): 430-436.
72. Khijwania, S. K., Tiwari, V. S., Yueh, F.-Y. and Singh, J. P. A fiber optic Raman sensor for hydrocarbon detection. Sensors and Actuators B:

Chemical. 2007. 125(2): 563-568.

73. Tomita, E., Kawahara, N., Nishiyama, A. and Shigenaga, M. In situ measurement of hydrocarbon fuel concentration near a spark plug in an engine cylinder using the 3.392 μm infrared laser absorption method: application to an actual engine. Measurement Science and Technology. 2003. 14(8): 1357.

74. Oshurko, V., Bykovsky, Y. A., Karpiouk, A. and Melekhov, A. Laser photoacoustic detection of oil hydrocarbons in water emulsions. LASER PHYSICS-LAWRENCE-. 2001. 11(4): 530-536.

75. Dewhurst, R., Hutchins, D., Palmer, S. and Scruby, C. Quantitative measurements of laser- generated acoustic waveforms. Journal of Applied Physics. 1982. 53(6): 4064-4071.

76. McDonald, F. A. Practical quantitative theory of photoacoustic pulse generation. Applied Physics Letters. 1989. 54(16): 1504-1506.

77. Mesaros, M., Martínez, O., Bilmes, G. and Tocho, J. Acoustic detection of laser induced melting of metals. Journal of applied physics. 1997. 81(2): 1014-1016.

78. Park, H. K., Grigoropoulos, C. P., Leung, W. P. and Tam, A. C. A practical excimer laser-based cleaning tool for removal of surface contaminants. Components, Packaging, and Manufacturing Technology, Part A, IEEE Transactions on. 1994. 17(4): 631-643.

79. Vogel, A., Schweiger, P., Frieser, A., Asiyo, M. N. and Birngruber, R. Intraocular Nd: YAG laser surgery: laser-tissue interaction, damage range, and reduction of collateral effects. Quantum Electronics, IEEE Journal of. 1990. 26(12): 2240-2260.

80. Teng, P., Nishioka, N., Anderson, R. and Deutsch, T. F. Acoustic studies of the role of immersion in plasma-mediated laser ablation. Quantum Electronics, IEEE Journal of. 1987. 23(10): 1845-1852.

81. Schilling, A., Yavaş, O., Bischof, J., Boneberg, J. and Leiderer, P. Absolute pressure measurements on a nanosecond time scale using surface plasmons. Applied physics letters. 1996. 69(27): 4159-4161.

82. Yavas, O., Schilling, A., Bischof, J., Boneberg, J. and Leiderer, P. Bubble nucleation and pressure generation during laser cleaning of surfaces. Applied Physics A: Materials Science & Processing. 1997. 64(4): 331-339.

83. White, R. Generation of elastic waves by transient surface heating. Journal of Applied Physics. 1963. 34(12): 3559-3567.

84. Park, H. K., Kim, D., Grigoropoulos, C. P. and Tam, A. C. Pressure generation and measurement in the rapid vaporization of water on a pulsed-laser- heated surface. Journal of applied Physics. 1996. 80(7): 4072-4081.

85. Bunkin, F. V., Kolomensky, A. A. and Mikhalevich, V. Lasers in Acoustics: Harwood Academic Publishers. 1991.

86. Bell, A. G. Upon the production of sound by radiant energy: Gibson Brothers, printers. 1881.

87. Rosencwaig, A. Photoacoustic spectroscopy. Advances in electronics and electron physics. 1978. 46: 207-311.

88. Askar'yan, G. and Moroz, E. Pressure on evaporation of matter in a radiation beam. Soviet Journal of Experimental and Theoretical Physics. 1963. 16: 1638.

89. Ashton, H. S. The modelling and application of pulsed laser photoacoustics for the detection of body analytes. Heriot-Watt University; 1999.

90. Schanke, T., Kjølberg, S. and Vogel, F. Oil in Water Monitoring for Subsea and Downhole Separators. Proceedings of the SPE/EPA/DOE Exploration and Production Environmental Conference. 2001: Society of Petroleum Engineers.

91. Freeborn, S. S. Pulsed Laser Photoacoustic instrumentation for the monitoring of crude oil in produced water. 1997.

92. Freeborn, S., Hannigan, J., Greig, F., Suttie, R. and MacKenzie, H. A pulsed photoacoustic instrument for the detection of crude oil concentrations in produced water. Review of scientific instruments. 1998. 69(11): 3948-3952.

93. BAR COHEN, Y. Non-destructive testing of microwelds using laserinduced shock waves', Brit. J. NDT. 1979. 21: 76-78.

94. Wellman, R. J. Laser System for the Detection of Flaws in Solids. DTIC Document. 1980.

95. Patel, C. and Tam, A. Pulsed optoacoustic spectroscopy of condensed matter. Reviews of Modern Physics. 1981. 53(3): 517.

96. Braslavsky, S. E. and Heibel, G. E. Time-resolved photothermal and photoacoustic methods applied to photoinduced processes in solution. Chemical reviews. 1992. 92(6): 1381-1410.

97. Hodgson, P., MacKenzie, H., Christison, G. and Quan, K. Laser photoacoustic detection of organic analytes in aqueous media. Near Infra-red Spectroscopy: Bridging the Gap between Data Analysis and NIR Applications (15th edition) Ellis Horwood. 1992: 407-412.

98. Christison, G. and MacKenzie, H. Laser photoacoustic determination of physiological glucose concentrations in human whole blood. Medical and Biological Engineering and Computing. 1993. 31(3): 284-290.

99. Liu, G. Theory of the photoacoustic effect in condensed matter. Applied optics. 1982. 21(5): 955-960.

100. Lai, H. and Young, K. Theory of the pulsed optoacoustic technique. The Journal of the Acoustical Society of America. 1982. 72(6): 2000-2007.

101. Heritier, J.-M. Electrostrictive limit and focusing effects in pulsed photoacoustic detection. Optics Communications. 1983. 44(4): 267-272.

102. Bunkin, F. and Komissarov, V. Optical excitation of sound waves(electrostriction and radiation absorption mechanisms). Soviet Physics-Acoustics. 1973. 19: 203-211.

103. Tam, A. and Leung, W. Measurement of small elastic anisotropy in solids using laser- induced ultrasonic pulses. Applied Physics Letters. 1984. 45(10): 1040-1042.

104. Park, S., Khan, M., Cheng, H. and Diebold, G. Photoacoustic effect in strongly absorbing fluids. Ultrasonics. 1991. 29(1): 63-67.

105. Komorowski, S. J. and Eyring, E. M. Pulse shapes of nanosecond photoacoustic signals in liquids detected by piezoelectric foil. Journal of applied physics. 1987. 62(7): 3066-3069.

106. Sullivan, B. and Tam, A. Profile of laser- produced acoustic pulse in a liquid. The Journal of the Acoustical Society of America. 1984. 75(2): 437-441.

107. Bae, Y., Song, J. and Kim, Y. Photoacoustic detection of nanosecond-pulse-induced optical absorption in solids. Applied optics. 1982. 21(1): 35-40.

108. Smith, R. A. Are hydrophones of diameter 0.5 mm small enough to characterise diagnostic ultrasound equipment? Physics in medicine and biology. 1989. 34(11): 1593.

109. Dumitras, D. C., Bratu, A. M. and Popa, C. CO2 Laser Photoacoustic Spectroscopy: I. Principles. Intech, Croatia. 2012: 3-42.

110. Beenen, A., Spanner, G. and Niessner, R. Photoacoustic depth-resolved

analysis of tissue models. Applied spectroscopy. 1997. 51(1): 51-57.

111. Laufer, J. G., Elwell, C. E., Delpy, D. T. and Beard, P. C. Pulsed near-infrared photoacoustic spectroscopy of blood. Proceedings of the Biomedical Optics 2004: International Society for Optics and Photonics. 57-68.

112. Sigrist, M. W., Bohren, A. M., Calasso, I. G., Naegele, M. and Romann, A. Sensitive and selective monitoring of trace gases by laser photoacoustic spectroscopy. Proceedings of the BiOS 2000 The International Symposium on Biomedical Optics: International Society for Optics and Photonics. 286-294.

113. Boschetti, A., Bassi, D., Iacob, E., Iannotta, S., Ricci, L. and Scotoni, M. Resonant photoacoustic simultaneous detection of methane and ethylene by means. of a 1.63-μm diode laser. Applied Physics B. 2002. 74(3): 273-278.

114. Bozóki, Z., Mohácsi, Á., Szabó, G., Bor, Z., Erdélyi, M., Chen, W. and Tittel, F. K. Near-infrared diode laser based spectroscopic detection of ammonia: A comparative study of photoacoustic and direct optical absorption methods. Applied spectroscopy. 2002. 56(6): 715-719.

115. Schilt, S., Thévenaz, L., Niklès, M., Emmenegger, L. and Hüglin, C. Ammonia monitoring at trace level using photoacoustic spectroscopy in industrial and environmental applications. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy. 2004. 60(14): 3259-3268.

116. Schramm, D., Sthel, M., Da Silva, M., Carneiro, L., Junior, A., Souza, A. and Vargas, H. Application of laser photoacoustic spectroscopy for the analysis of gas samples emitted by diesel engines. Infrared physics & technology. 2003. 44(4): 263-269.

117. Reddy, K., Slifkin, M. and Weiss, A. Characterization of inorganic materials with photoacoustic spectrophotometry. Optical Materials. 2001. 16(1): 87-91.

118. Schlageter, B., Pörting, S., Strassburger, J., Moreno-Bondi, M., Braslavsky, S., Oliveros, E. and Braun, A. Development of an optoacoustic sensor module for pH and/or CO2 determination in aqueous solutions. Sensors and Actuators B: Chemical. 1997. 39(1): 443-447.

119. Foster, N., Amonette, J., Autrey, T. and Ho, J. Detection of trace levels of water in oil by photoacoustic spectroscopy. Sensors and Actuators B: Chemical. 2001. 77(3): 620-624.

120. Wan, J., Ioffe, M. and Depew, M. A novel acoustic sensing system for on-

line hydrogen measurements. Sensors and Actuators B: Chemical. 1996. 32(3): 233-237.

121. Schmidt, K. and Beckmann, D. Biomass monitoring using the photoacoustic effect. Sensors and Actuators B: Chemical. 1998. 51(1): 261-267.

122. Hutchins, D. Ultrasonic generation by pulsed lasers. Physical Acoustics. 1988. 18: 21-123.

123. Scruby, C. B. and Drain, L. E. Laser ultrasonics techniques and applications: CRC Press. 1990.

124. White, D., Curry, G. and Stevenson, R. The acoustic characteristics of the skull. Ultrasound in medicine & biology. 1978. 4(3): 225-252.

125. Krishnaswamy, S. Theory and applications of laser-ultrasonic techniques. Ultrasonic Nondestructive Evaluation: Engineering and Biological Material Characterization. 2003: 435-494.

126. Murray, T. W. and Wagner, J. W. Laser generation of acoustic waves in the ablative regime. Journal of applied physics. 1999. 85(4): 2031-2040.

127. Scruby, C., Dewhurst, R., Hutchins, D. and Palmer, S. Quantitative studies of thermally generated elastic waves in laser- irradiated metals. Journal of Applied Physics. 1980. 51(12): 6210-6216.

128. Achenbach, J. Wave propagation in elastic solids: Elsevier. 1984.

129. Rose, L. Point- source representation for laser- generated ultrasound. The Journal of the Acoustical Society of America. 1984. 75(3): 723-732.

130. Spicer, J. B. Laser ultrasonics in finite structures: comprehensive modelling with supporting experiment. thesis (ph.d.)--the johns hopkins university, Dissertation Abstracts International,. 1991. 52-06(Section: B): 3242.

131. Thomsen, C., Grahn, H., Maris, H. and Tauc, J. Ultrasonic experiments with picosecond time resolution. Le Journal de Physique Colloques. 1985. 46(C10): C10-765-C710-772.

132. Thomsen, C., Grahn, H. T., Maris, H. J. and Tauc, J. Surface generation and detection of phonons by picosecond light pulses. Physical Review B. 1986. 34(6): 4129.

133. Rogers, J. A., Maznev, A. A., Banet, M. J. and Nelson, K. A. Optical generation and characterization of acoustic waves in thin films: Fundamentals and applications. Annual Review of Materials Science. 2000. 30(1): 117-157.

134. Hernandez, C. M., Murray, T. W. and Krishnaswamy, S. Photoacoustic characterization of the mechanical properties of thin films. Applied physics letters. 2002. 80(4): 691-693.

135. Cleveland R. O., a. M. J. A. Extracorporeal Shock Wave Lithotripsy. The Physics of Shock Wave Lithotripsy. 2000. 4(38): 315-332.

136. Brown, A. Ultrasonic spectroscopy. Ultrasonic testing: Non-conventional testing techniques.(A 82-42726 21-35) Chichester, Sussex, England and New York, Wiley-Interscience, 1982. 1982: 167-215.

137. Felix, M. and Ellis, A. Laser- Induced Liquid Breakdown- a Step- By- Step Account. Applied physics letters. 1971. 19(11): 484-486.

138. Bell, C. and Landt, J. Laser- induced high- pressure shock waves in water. Applied Physics Letters. 1967. 10(2): 46-48.

139. Emmony, D., Geerken, T. and Klein- Baltink, H. Laser- generated high- frequency sound waves in water. The Journal of the Acoustical Society of America. 1983. 73(1): 220-224.

140. Sigrist, M. W. Air monitoring by spectroscopic techniques, Vol. 127: John Wiley & Sons. 1994.

141. Carome, E., Clark, N. and Moeller, C. Generation of acoustic signals in liquids by Ruby laser-induced thermal stress transients. Applied Physics Letters. 1964. 4(6): 95-97.

142. Rice, M., McQueen, R. G. and Walsh, J. Compression of solids by strong shock waves. Solid state physics. 1958. 6: 1-63.

143. Huff, C. and Graham, R. Pressure measurements very near an electrical arc discharge in a liquid using a lithium niobate piezoelectric transducer. Applied Physics Letters. 1975. 27(4): 163-164.

144. Sigrist, M. W. and Kneubühl, F. K. Laser- generated stress waves in liquids. The Journal of the Acoustical Society of America. 1978. 64(6): 1652-1663.

145. Bushanam, G. S. Laser- generated thermoelastic shock wave in liquids. Journal of Applied Physics. 1975. 46(5): 2074-2082.

146. Davidson, G. and Emmony, D. A schlieren probe method for the measurement of the refractive index profile of a shock wave in a fluid. Journal of Physics E: Scientific Instruments. 1980. 13(1): 92.

147. Vedam, K. and Limsuwan, P. Piezo- and elasto- optic properties of liquids under high pressure. II. Refractive index vs density. The Journal of Chemical

Physics. 1978. 69(11): 4772-4778.

148. Anderson, J. D. Modern compressible flow with historical perspective. 2003.

149. Stokes, G. On a Difficulty in the Theory of Sound. Classic Papers in Shock Compression Science: Springer. 71-81; 1998.

150. Walsh, J. M. and Rice, M. H. Dynamic compression of liquids from measurements on strong shock waves. The Journal of Chemical Physics. 1957. 26(4): 815-823.

151. Al'Tshuler, L., Bakanova, A. and Trunin, R. Phase transformations of water compressed by strong shock waves. Proceedings of the Soviet Physics Doklady. 761.

152. Nagayama, K., Mori, Y., Shimada, K. and Nakahara, M. Shock Hugoniot compression curve for water up to 1 GPa by using a compressed gas gun. Journal of applied physics. 2002. 91(1): 476-482.

153. Mitchell, A. and Nellis, W. Equation of state and electrical conductivity of water and ammonia shocked to the 100 GPa (1 Mbar) pressure range. The Journal of Chemical Physics. 1982. 76(12): 6273-6281.

154. Borin, A. and Poppi, R. J. Multivariate quality control of lubricating oils using Fourier transform infrared spectroscopy. Journal of the Brazilian Chemical Society. 2004. 15(4): 570-576.

155. Gillespie, B. M., Sarli, M. S. and Smith, K. W. Manufacture of lube base stock oil. Google Patents. 1980.

156. Bigelow, P. How to make standard solutions for chemistry. 2010.

157. Bidin, N. Studies on laser induced cavitation erosion and mechanism of cavitation damage. Universiti Teknologi Malaysia, Faculty of Science; 1995.

158. Ali, A. H. and Bidin, N. Plasma formation induced by a Q-switched Nd: YAG laser. Jurnal Fizik Malaysia. 2004. 25(1-2): 33-41.

159. Del Grosso, V. and Mader, C. Speed of sound in pure water. The Journal of the Acoustical Society of America. 1972. 52(5B): 1442-1446.

160. Company, L. P. Nitrogen Laser Operating Manual, LN120C.

161. Davarcioglu, B. An Overview of Diode Pumped Solid State (DPSS) Lasers. Facultyof Science and Art, Department of Physics, Aksaray-TURKEY. 2010.

162. Willett, C. S. Introduction to gas lasers: population inversion mechanisms with emphasis on selective excitation processes. Oxford Pergamon Press International Series on Natural Philosophy. 1974. 67.

163. Mariani Idroas, R. G. G. a. M. N. I. Journal of Electrical Engineering,UTM. June 2006.