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An aerodynamic study of a micro scale vertical axis wind turbine

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Abstract

The utilization of wind to generate power provides an alternative and renewable energy source compared to current fossil fuels based power generation. The world's fossil fuel energy is finite and is depleting at a faster rate. Moreover, the fossil fuel is directly related to air pollution, land and water degradation. Despite significant progresses have been made in power generation using large scale wind turbines recently, domestic scale wind turbines especially vertical scale wind turbines have been received less attention which have immense potentials for standalone power generation. This paper examines the aerodynamic advantages of a novel prototype vertical axis wind turbine that can be used for power generation in built up areas.

Keywords: Wind turbine; aerodynamics; efficiency; power generation; wind characteristics.

1. Introduction

The rising greenhouse gas emission from fossil fuel energy resources and the uncertainty of energy supplies have forced to explore alternative renewable energy sources for power generation. Most developed including Australia and emerging economies adopted a renewable energy target. Power extraction from wind has achieved significant improvement over the decade, making it more economically competitive over other renewable energy sources for power generation.

The wind power is abundant, renewable, widely distributed, clean, produces no greenhouse gas emissions during operation and uses little precious land [3, 4, 9, 10]. Any effects on the environment are generally less problematic than those from other energy sources. As of 2010, wind energy production was over 2.5% of worldwide power, growing at more than 25% per annum. Thanks to the technological advances and better understanding of wind characteristics, the overall generation cost per unit of energy has come down to the cost of power generated by using high grade coals and/or natural gas [2, 5, 6, 7].

In 2010 and 2011, more than half of all new power generation from the wind was added for the first time outside of Europe and North America. China and India lead the construction of wind turbines for power generation, accounting over half of the world's total new wind turbine installations [7]. Over the past five years the average growth of new wind turbine installations is estimated to be over 27.6% each year. The world's top eleven countries that generated power from the wind in 2011 are shown in Fig. 1.

Currently two types of wind turbines: a) horizontal axis wind turbines (HAWTs) and b) vertical axis wind turbines (VAWTs) are widely used to generate electricity. Both types of turbine have been tested and optimized in smooth flows –

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usually in wind tunnels or in computations fluid dynamic domains. However, their performances can significantly differ in situ from the predicted performances.

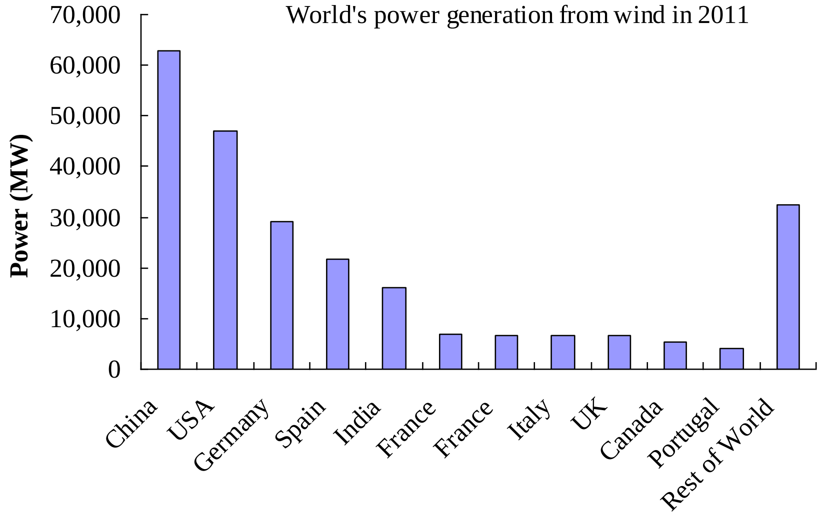
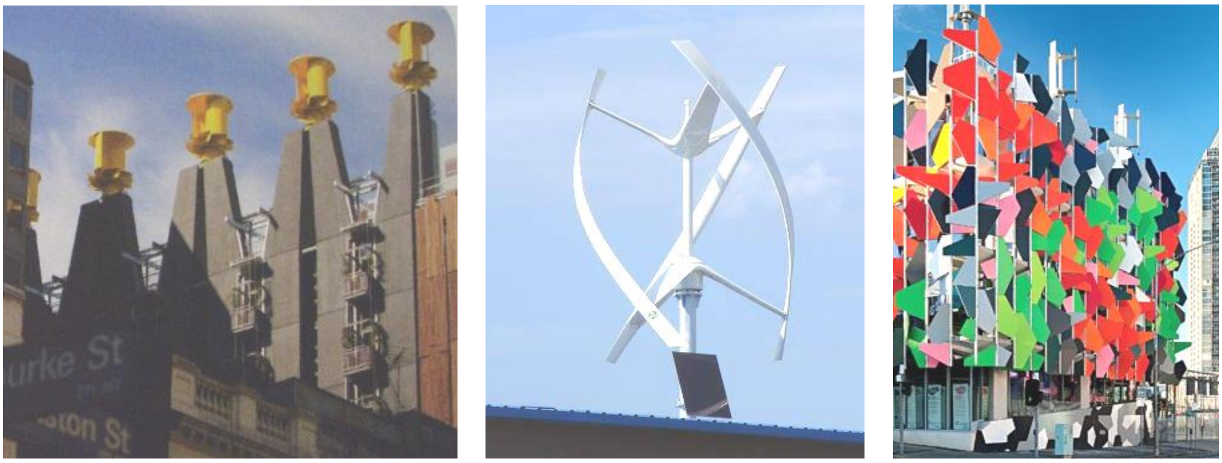


Fig. 1. Top ten wind power generating countries by December 2011 [6, 7].

China has become world's largest manufacturer of wind turbines ranging from large scale to domestic scale. The power output of a domestic scale or micro scale wind turbine is generally less than 10 kW. One of the difficulties for the application of domestic scale wind turbines in urban environment is the complex wind characteristics due to the presence of buildings and structures. In urban areas close to the ground the atmospheric wind is highly turbulent and this is particularly strong in close proximity of buildings. Turbulence exhibits significant fluctuations in magnitude and high directional variability. Under such conditions the VAWT is a more effective power generator than the HAWT. Generally, VAWTs possess fewer moving parts and a lower tip speed ratio than HAWTs making VAWTs significantly quieter and thus well-suited for urban applications. Unlike HAWTs, which have to continuously 'yaw' (rotate about the vertical axis) into the ever-changing wind direction, VAWTs are less sensitive to changing wind directions and therefore to turbulence. This is an important advantage for the effective use of VAWTs in urban and built environments [1]. However, most domestic scale VAWTs and HAWTs are not efficient and do not perform well as they are being developed by wind energy enthusiasts and small companies who generally do not have adequate technological and financial resources to refine their initial designs to perform better by increasing efficiency [1]. A few savonius type VAWT require a motor to get them up to operating speed. Some ornamental domestic scale wind turbines are shown in Fig. 2. Apart from aesthetic, these turbines hardly produce any measurable power.



a) VAWTs on CH2 building b) Savonius type VAWT c) Nautilus (Darrieus) rotors

Fig. 2. Various domestic scale wind turbines used in Australia [1].

In this paper, we propose a new concept of a vertical axis wind turbine which is capable to operate at a wider range of wind speeds with much higher efficiency. The concept of this turbine has been developed by Wind Energy Technologies Pty Ltd Australia. It has overcome one of the major limitations of current VAWTs. As the airflow moves through the rotor of VAWT, it has to negotiate the rotating vanes at the rear. In so doing it imparts a negative torque on the rotor. The domestic scale vertical axis wind turbine developed by the Wind Energy Technologies Pty Ltd Australia used a shroud which diverts the wind from the rear of the vanes of the rotor. The device simultaneously shields parts of the rotor from the wind, whilst directing it to those parts where it can more efficiently impart momentum to the rotor. The prototype model is shown in Fig. 3. The device has been patented in Australia by the Wind Energy Technologies Pty Ltd Australia. The primary objective of this paper is to undertake experimental investigations in the wind tunnel environment as part of a large scale research project of domestic scale wind turbines in the School of Aerospace, Mechanical and Manufacturing Engineering in partnership with the Wind Energy Technologies Pty Ltd. The dimensions of the developed prototype turbine are not given here due to confidentiality.

2. Methods

The experimental investigation was undertaken in RMIT Industrial Wind Tunnel under a range of wind speeds. The wind tunnel is a closed return circuit with a rectangular test section (3 m width, 2 m height and 9 m length). The maximum air speed of the tunnel is approximately 150 km/h. More details about the tunnel can be found in [11]. The experimental set up in RMIT Industrial Wind Tunnel is shown in Fig. 3. Prior to wind tunnel testing, some preliminary CFD investigations were also undertaken to understand the basic concept of the design. However, the CFD results were not included here. The rotational speed of the turbine was initially tested using a free standing pedal fan. This finding was later verified with the wind tunnel data.

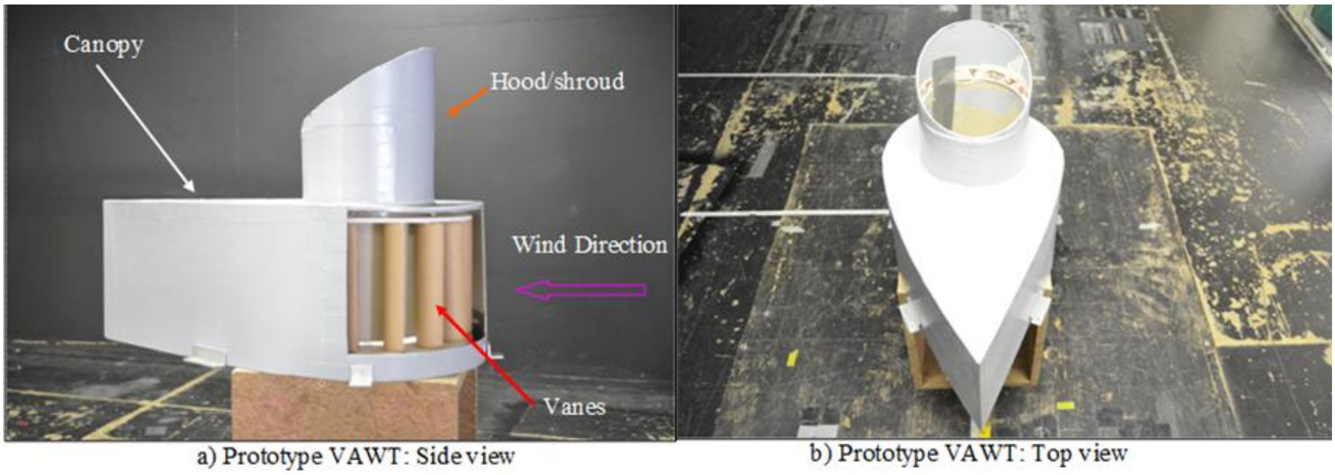


Fig. 3. A prototype developed by Wind Energy Technologies is in the test section of RMIT Industrial Wind Tunnel.

3. Results

The prototype was tested with two configurations. The first configuration was the bare rotor without the shroud (cowl) and the 2nd configuration was the bare rotor shrouded with a cowl. Both configurations were investigated at wind speeds ranging from 5 km/h (1.4 m/s) to 30 km/h (8.33 m/s). Due to fragility, the higher wind speed was not attempted. However, a new model has been under construction which will allow the prototype to be tested at a much higher speed (~100 km/h).

The rotational speed of the rotor was measured as a function of wind speeds which are shown in Figs. 4 and 5. Fig. 4 shows the variation of spinning rate (rotational speed) with the wind speed of the turbine with and without the cowl. The figure clearly indicates that the cowling has increased the spin rate of the turbine more than double at all wind speeds tested.

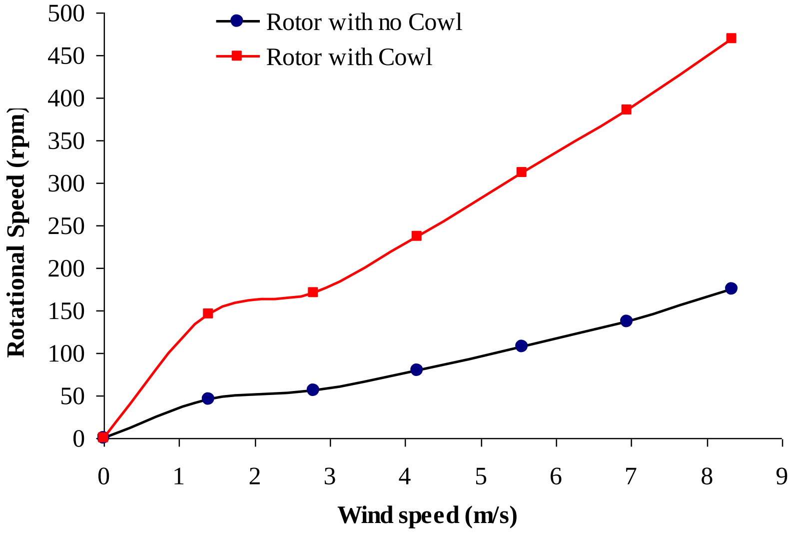


Fig.4. Spin rate of the rotor as a function of wind speeds.

The spin rate of the turbine with and without cowl achieved using a free standing pedal fan is shown in Fig. 5. Although the flow condition is significantly inferior compared to the wind tunnel environment, it is clearly shows the trend that the cowling has notable impact as it reduces the resistance on the rare blade. The wind speed range achieved by the pedal fan was from 10 km/h to 20 km/h. The figure visibly demonstrates that the cowl has increased the spinning rate over two compared to the bare rotor.

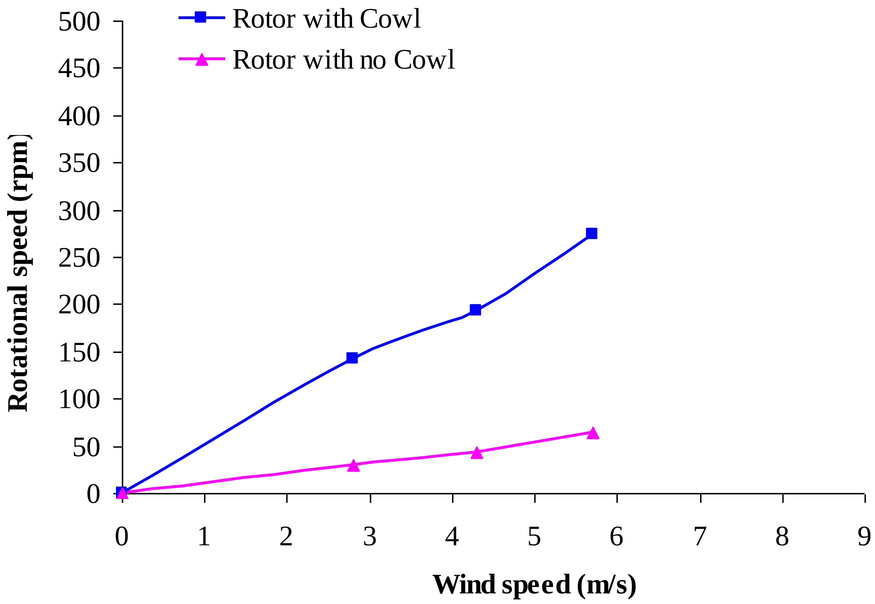


Fig.5. Spin rate of the rotor as a function of wind speeds (using pedal fan).

4. Discussion

The performance of a wind turbine is measured by its power curve. The work is currently underway to develop the power curve of the prototype over a range of wind speeds. The spinning rate is indicative only. A thorough and in-depth study is needed to establish the full potential of the prototype. A wind turbine that shows good performance in a controlled environment such as wind tunnel does not necessarily performs well in situ as the wind characteristics in urban (built up) areas significantly vary compared to rural and unobstructed areas. At present, there is no prediction model for wind characteristics of built up areas that can be used with confidence to estimate the wind profile (wind velocity, wind direction, wind gustiness & turbulence intensities, etc.) as the urban areas are very diverse and substantially dynamic. Most currently available wind data lacks the required resolution and practically invalid for heights less than 10 m. For example, the wind data determined through modeling for the city of Melbourne, Australia is available at an elevation of 25 m which is an impractical height for most urban dwellings as a mast that high would make it difficult to get planning permission. Additionally, most Australian metropolitan cities except the city centre are being developed where the heights of dwellings are less than 10 m. In order to maximize the use of wind resources for power generation using a wind turbine in urban areas, the wind flow around a typical house/building, both in isolation and within an array of houses with different configurations needs to be understood. Once the wind behavior is understood, the potential site and a guide or a recommendation for installing wind turbines can be determined. It should be stressed that the complexity of modeling the urban environment using computational models has severe limitations and results can only be considered over simplified but nonetheless, gives an indication of expected yields within the built environment [3, 4, 10]. The understanding of micro wind environments is required for the appropriate site selection.

To investigate the real performance in situ, the prototype turbine needs to be monitored over a long period and refine the performance by undertaking further design change. The turbine's fatigue life, payback period and noise level are also required to be assessed as the service life and wider acceptability largely depend on their important criteria.

5. Concluding remarks

The domestic scale wind turbines have immense potential for wind power generation in built up areas. With current commercial domestic scale wind turbines, it is difficult to generate any appreciable power due to their poor performance in situ. However, the prototype developed by Wind Energy Technologies has shown to be promising. In order understand its overall performance and economic viability, a comprehensive study is required. The in situ performance data needs to be reconciled with the wind tunnel data along with the appropriate mounting site selection. The site selection cannot be relied on simulated data only. Government policies and regulations are required to be enacted for better utilization of domestic scale/micro wind turbines. Significant research and development are required for improving the efficiency and power generation capacity of domestic scale wind turbines. As majority small wind turbine manufacturers are small companies and/or wind turbine enthusiasts, public and large companies' financial investments in this important sector are essential.

References

[1] Ali, A., Alam, F., Djamovski, V., Watkins, S., 2011. A review of power generation from wind in Australia, in "Proceedings of the 9th International Conference of Mechanical Engineering (ICME2011)". Bangladesh University of Engineering and Technology, Dhaka.
[2] BTM Forecasts 340-GW of Wind Energy by 2013, 2012. [Retrieved from http://www.renewableenergyworld.com, on 29 August 2012].
[3] Clean Energy Council, Clean Energy Australia Annual Report, 2010. [Retrieved from http://www.cleanenergycouncil.org.au]
[4] Diesendorf, M., 2003. Australia's polluting power: coal fired electricity and its impact on global warming, [Retrieved on 11 March 2011 from www.wwf.org.au].
[5] Fthenakis, V., Kim, H. C., 2009. Land use and electricity generation: A life-cycle analysis, Renewable and Sustainable Energy Reviews 13(6-7), p. 1465.
[6] GWEC, Global Wind Report Annual Market Update, 2012. [Retrieved from http://www.gwec.net/index.php?id=180, on 14 May 2012].
[7] GWEC, Global Wind Energy Outlook, 2012. [Retrieved from http://www.gwec.net/index.php?id=181&L=0%B4, on 14 May 2012].
[8] Gipe, P., 2009. Wind energy basics: a guide to home and community scale wind energy systems, Chelsea Green Publishing, USA.
[9] Nixon, N., 2012. The history of wind power. [Retrieved from http://www.guardian.co.uk/environment, on 10 April 2012].
[10] Yusaf, T., Goh, S., Borserio, J. A., 2011. Potential of renewable energy alternatives in Australia, Renewable and Sustainable Energy Reviews 15, p. 2214.
[11] Alam, F., Zimmer, G., Watkins, S., 2003. Mean and time-varying flow measurements on the surface of a family of idealized road vehicles, Exp. Therm. Fluid Sc. 27(5), p. 639.

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Thermal recycling of solid tire wastes for alternative liquid fuel: the first commercial step in Bangladesh

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Abstract

The first small scale commercial tire waste pyrolysis plant has been installed by the Radiant Renewable Energy (RRE) Ltd. at Gazipur, Dhaka for reducing liquid fuel crisis in Bangladesh. The plant has two pyrolysis unit, each of them consists of a horizontal axis rotary type batch mode reactor with a recycling capacity of 4.5 tons/run. Solid tire wastes in half/whole size are feed into the reactor chamber, operating at 420^{o}C with a light over-pressure of 0.03 bar. The reactor is heated externally by burning product pyrolysis liquids for first three hours and by burning product pyro-gas for rest five hours. The products distribution at optimum reactor operating condition were found oil: 45 wt%, char: 35 wt%, and gases: 10 wt%, in addition to the steel cords: 10 wt% of solid tire waste. The product liquids have been found to have a high gross calorific value (GCV) of around 44 MJ/kg, which would encourage their use as replacements for conventional liquid fuels. Pyrolytic char may be used as a solid fuel, activated carbon, priters ink etc. Pyrolysis gas contains high concentrations of methane, ethane, butadiene and other hydrocarbon gases with a GCV of approximately 37 MJ/m^3, a value sufficient to provide the energy required by the tire pyrolysis process. However, the presented plant should be followed some recommended pionts for better operation and its further extension, and also for our sincere corner to safe environment. The plant can be run only under continuous monitoring and consultancy support of a tire pyrolysis specialist team because of new technology and waste material concern.

Keywords: Solid tire wastes, first small scale commercial plant, alternative liuid fuels

Nomenclature

B/RT	bicycle / rickshaw tire
GC/MS	gas cromatography / mass spectrometry
GOB	government of Bangladesh
$K_{1\ldots3}$	reaction kinetics
MT	motorcycle tire
PCT	passenger car tire
PM	particulate matter
TG/DTG	thermalgravimetry/differential thermalgravimetry
TT	truck tire
VOC	volatile organic compounds
kgOE	kilogram of oil equivalent
MTOE	million ton of oil equivalent

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1. Introduction

The standard of living and quality of life of a nation depend on its per capita energy consumption. Bangladesh a developing country, and is one of the most densely populated (914 persons/km^2) countries in the world, with a total population of 135 million. Bangladesh's per capita energy consumption is very low, the lowest within the Indian subcontinent. The 2005 energy consumption value stands at 227 kgOE, compared to 512 kgOE for India, 490 kgOE for Pakistan, 478 kgOE for Sri Lanka and 450 kgOE for South Asia, and it was much below the world average of 1778 kgOE. Total primary energy consumption in 2004 was 30.70 MTOE and the energy consumption mix was estimated as: indigenous biomass 60%, indigenous natural gas 27.45%, imported oil 11.89%, imported coal 0.44% and hydro 0.23%. More than 77% of the country's population lives in rural areas, meting most of their energy needs from traditional biomass fuels. Around 32% have access to electricity, while in rural areas the availability of electricity is only 22%. Only 3-4% of the households have connection of natural gas for cooking purposes. Only about 2-3% households use kerosene for the same purpose and the rest (over 90%) of people depend on biomass for their energy needs. Thus it is crucial to find out alternative and sustainable resources to mitigate the energy crisis in Bangladesh.

It is estimated that about 90,000 metric tons tires become scrap and are disposed of every year in Bangladesh [1]. The disposal of non-biodegradable solid tire wastes from human activity is a growing environmental problem for the modern society, especially in developing countries. Unfortunately, most of these scrap tires are simply dumped under open sky and in landfills in developing countries. Open dumping may result in accidental fires with highly toxic emissions or may act as ideal breeding grounds for disease carrying mosquitoes and other vermin with the aid of rain water. Landfills full of tires are not acceptable to the environment because tires do not easily degrade naturally. In recent years, many attempts have been made to find new ways to recycle tires:

- Reconstruction of waste tires
- Shredding or grinding and crumbling to recycle rubber powders
- Incineration to supply thermal energy in utility boilers to produce electricity, in cement kilns and brick fields
- Utilisation in building applications
- Landfilling, heaping and abandonment and
- Other treatments

However, grinding is quite expensive because it is performed at cryogenic temperatures and requires energy-intensive mechanical equipment, while incineration may produce hazardous polycyclic aromatic hydrocarbons (PAHs) and soot during the combustion process.

Pyrolysis as an attractive method to recycle scrap tires has recently been the subject of renewed interest. Pyrolysis of tires can produce oils, chars, and gases, in addition to the steel cords, all of which have the potential to be recycled. Tire pyrolysis liquids (a mixture of paraffins, olefins and aromatic compounds) have been found to have a high gross calorific value (GCV) of around 41-44 MJ/kg, which would encourage their use as replacements for conventional liquid fuels [2-10]. In addition to their use as fuels, the liquids have been shown to be a potential source of light aromatics such as benzene, toluene and xylene (BTX), which command a higher market value than the raw oils [2-4, 8, 11-13]. Similarly, the liquids have been shown to contain monoterpenes such as limonene [1-methyl-4-(1-methylethenyl)-cyclohexene], a high value light hydrocarbon. Pyrolytic char may be used as a solid fuel or as a precursor for the manufacture of activated carbon [2, 8, 10, 14]. Roy et al. [9] found that another potentially important end-use of the pyrolytic carbon black (CBp) may be as an additive for road bitumen. Furthermore, active carbons were prepared from used tires and their characteristics were investigated by Roy et al. [9], Zabaniotou and Stavropoulos [15], and Zabaniotou et al. [16]. Some of the previous research groups [2, 4, 8, 11, 17] studied the composition of evolved pyrolysis gas fraction and reported that it contains high concentrations of methane, ethane, butadiene and other hydrocarbon gases with a GCV of approximately 37 MJ/m^3, a value sufficient to provide the energy required by the pyrolysis process.

Very different experimental procedures have been using to obtain liquid products from tire wastes by pyrolysis technology including fixed-bed reactors [3, 4, 8, 11, 18-28], fluidized-bed pyrolysis units [6, 29], vacuum pyrolysis units [7, 9, 30-31], spouted-bed reactors [32], etc. all over the world for the last two decades. Within the past ten years, research and development works have also been carried out for the fixed-bed fire-tube heating pyrolysis reactor system at Rajshahi University of Engineering & Technology (RUET). Pyrolysis of various organic solid wastes in the fixed-bed fire-tube heating pyrolysis reactor have been successfully completed and the results are published elsewhere [33-39].

The Radiant Renewable Energy (RRE) Ltd. has installed a small commercial scale pyrolysis plant at Kainzanul, Vawal Mirzapur, Gazipur, Dhaka to take part as a potential contributor for mitigating liquid fuel crisis in Bangladesh. The pyrolysis technology for production of alternative liquid fuel from solid tire waste is new in Bangladesh and it is the first commercial plant in the country. The RRE Ltd. has applied for consultancy support to the Department of Mechanical Engineering of RUET for better operation and extension of its plant, and also for pyro-products quality improvement and new usages of the products. It is, however, to be noted that many problems, both technical and operational, need to be solved before the said process could satisfy the reliability and economic conditions set forth by the world market.

2. The tire waste pyrolysis process

Pyrolysis, essentially an endothermic process, an environmentally attractive method for the treatment of tire wastes. The process uses medium temperatures (400 ~ 500^oC) and an oxygen-free environment to decompose solid tire wastes chemically, thus producing minimum emissions of nitrogen oxide and sulphur oxide compared to the commonly practised conventional technology, incineration. Pyrolysis also allows valuable materials to be recovered.

Pyrolysis is a thermal degradation process in which the solid tire waste is heated indirectly in an oxygen-free atmosphere. The whole process is the sum of a series of parallel and subsequent reactions that take place in the pyrolysis reactor. The most common rubbers used for tires are natural rubber (NR), styrene-butadiene rubber (SBR) and butadiene rubber (BR). The rubbers consist mostly of blends of two or three rubbers, together with minor constituents including oil, plasticizer, and other additives. All of these constituents lose their weight at different rates and at different temperatures when pyrolysed. A review of the available international literature and the laboratory results show that the decomposition temperature is about 150-350^oC for processing oils, plasticizer, and other organic additives, 330-400^oC for NR, and 400-480^oC for SBR and BR.

A flow diagram of tire pyrolysis process, including the proposed thermal decomposition model, is presented in Fig. 1. The three types of arrows in the flow diagram indicate three decomposition reactions. The higher weight or color deepness of the arrows indicates the decomposition of the corresponding tire material in the higher temperature regions.

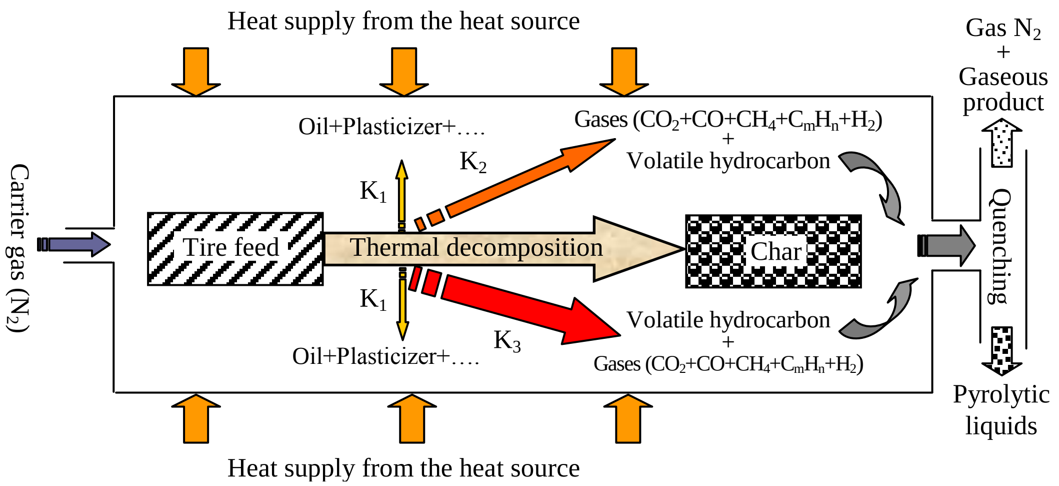

Fig. 1. Flow diagram of tire pyrolysis process including the proposed thermal decomposition model

Thus, the global pyrolysis reaction that takes place into a reactor can be described in the following manner:

- Tire wastes →volatile hydrocarbon + gases + solid residues
- Tire wastes, fed into the pyrolysis reactor undergoes a thermal cracking, by cleaving itself into volatile hydrocarbon, gases and solid residue.
- Volatile hydrocarbon can be cooled and condensed into a liquid fraction
- Gaseous fraction remains uncondensed during quenching
- Solid residues wait in the reactor chamber for their removal

Normally, the process provides:

- A gaseous fraction (10 – 15 wt%) essentially composed of CH_4, and higher hydrocarbons C_mH_n, H_2, CO_2, CO etc.
- A liquid fraction (40 – 45 wt%), composed of water, tar and oils (organic compounds);
- Solid residues containing steel cord (10 – 12 wt%) and char (30 – 35 wt%), containing fixed carbon and ashes (metals, oxides and inert matter).

Thermal decomposition (pyrolysis) behaviour for a typical solid tire waste at tow different heating rates are presented in Fig. 2. The TG and DTG curves show that the volatile fraction completely decomposed within the reactor temperature below 500^oC and the decomposition rate is maximum around 400^oC.

3. Brief description of the small commercial scale pyrolysis plant at RRE Ltd.

The Radiant Renewable Energy Ltd. has installed a small commercial scale pyrolysis plant on more or less one acre land at Kainzanul, Vawal Mirzapur, Gazipur, Dhaka. Its main office is located at House No.: 44, Road No.: 03, Sector: 13, Uttara

Model town, Dhaka - 1230 that is about 30 km far from the plant. The plant is situated in a populated village area and is surrounded by many living houses, a mosque, a road and a playground. However, the plant yard is devided into four sections:

(i) Main plant section
(ii) Plant site office houses
(iii) Warehouse
(iv) Tire wastes stock site

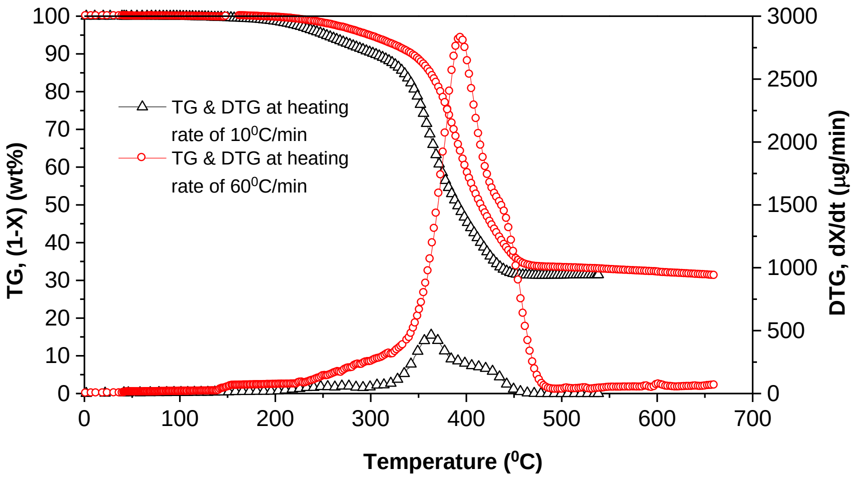

Fig. 2. TG and DTG plots for a typical tire waste at heating rates of 10 and 60°C/min

There are two pyrolysis unit each of capacity 4.50 tons solid tire wastes per run in the Radiant Renewable Energy Ltd. Each pyrolysis unit consists of the folowing main systems with some accessories and mountings:

(i) A horizontal axis rotary type batch mode reactor
(ii) Furnace
(iii) Atmolysis tower
(iv) Condensers
(v) Fractionating column
(vi) Gas condenser
(vii) Cooling water tank
(viii) Gas-oil seperator
(ix) Oil-water separator
(x) Gas-water separator

Acesories:

(i) Flue gas treatment and exhaust systems
(ii) Liquid handling and storage systems
(iii) Cooling water supply pumps
(iv) Water cooling pond
(v) Three generators for supplying electricity for lighting and water pumps

Mountings:

(i) Thermometer
(ii) Pressure gage
(iii) Oil-gas vavle
(iv) Steam vavle
(v) Observation port
(vi) Check vavle
(vii) Emergency exhaust valve
(viii) Gas outlet valve
(ix) Back-fire relief valve
(x) Gas valve

Each pyrolysis unit consists of a horizontal axis rotary (15 rph) type batch mode reactor (37.50 dm^3 in volume and 2.0 m in diameter). Solid tire wastes in half/whole size are feed into the reactor chamber manually and then leackage is checked by compressed air at a pressure of 5~6 kg_f/cm^2 (5~6 bar). The reactor working with a light over-pressure (maximum working pressure of 300 mm w.c./0.03 bar) is heated externally by burning product pyrolysis liquids for first three hours and burning product pyro-gas for rest five hours. Temperature inside the reactor is raised up to 420^{o}C, hold it at this temperature for 5 hours and then whole reactor systen is cooled down by natural cooling for more or less 10 hours.

The heating system consists of a furnace under the reactor drum. The provision for burning both liquid and gasious fuels are equipt in the furnace. The reactor drum is surrounded by a annular space that is covered by insulating cage. The produced hot gases pass through the annular space between reactor drum and insulating cage, and provide sufficient energy for pyrolysis reaction. The process temperature vs time plot is shown in Fig. 3.

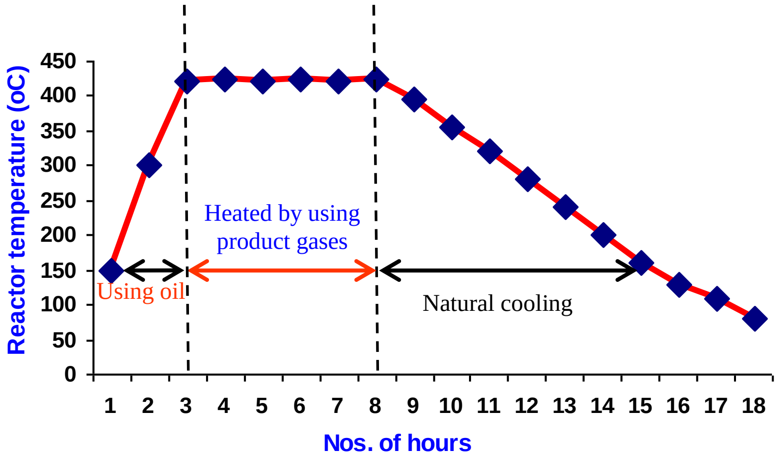

Fig. 3: Reactor temperature distribution during heating and cooling

The vapour condensation system consists of five components: a jacketed atmolysis towers - that removes tars and heavy fraction, condenser and fractionating column – that cool and further seperate vapor from heaver fraction, gas condenser and cooling water tank – that condense vapor into pro-liquids. The product liquid and gas mixture are then pass through gas-oil seperator, oil-water separator and gas-water separator - that remove light fraction and cool the gaseous stream further to about 30^{o}C. Steel and char (carbon black) are collected manually. When the reactor is cooled well below 70^{o}C the reactor drum is open, and steel cord and char are removed manually. The char fraction is found inside the reactor in powdered form and seperated from steel cord because of continuous rotation of the reactor drum.

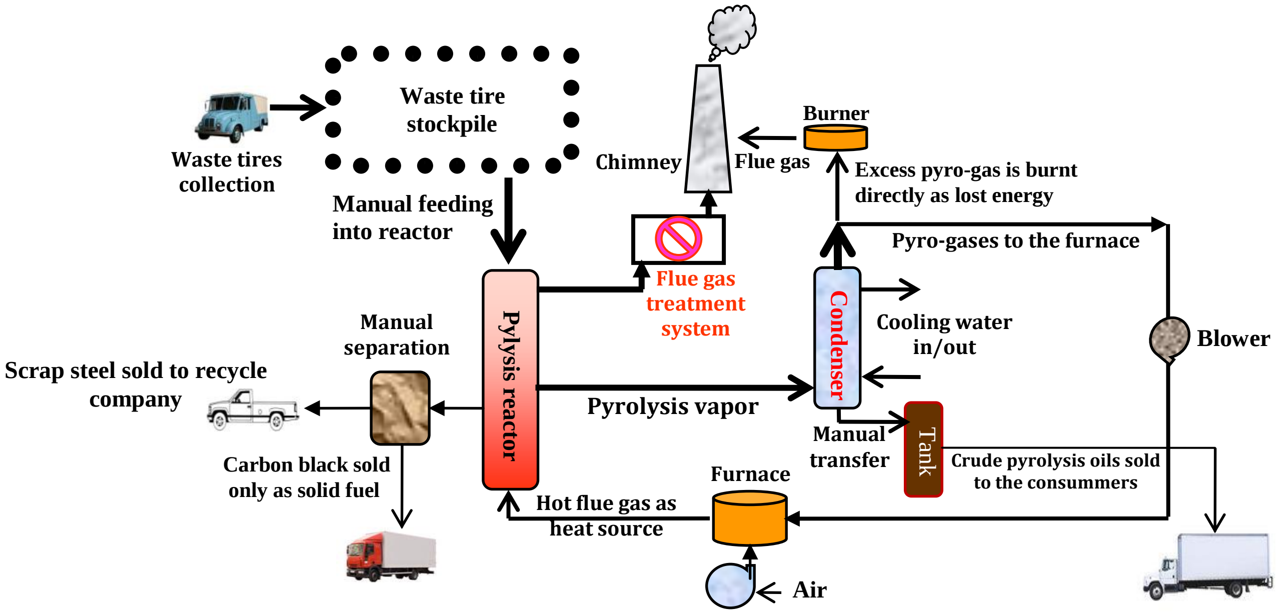

Fig. 4: Material and energy flow diagram for the tire waste pyrolysis plant installed by RRE Ltd. in Gazipur

Flue gas exhaust system for each pyrolysis unit consists of a wet-scruber, a draught fan and a chimney. The flue gas are filtered in two demister filters (to be incorporated) to separate particulate matter, and pass through a wet-scrubbing system designed to remove acid components by CaOH/NaOH column. After that the flue gas is exghausted into the atmosphere. The material and energy flow diagram for the plant at RRE Ltd. is shown in Fig. 4.

3.1 Tire wastes found in the Radiant Renewable Energy Ltd. pyrolysis plant

There are many different manufacturers and countless different types and formulations available in the marketplace; the composition of the tires varies depending on the tire grade, age and manufacturers. The Radiant Renewable Energy Ltd. collects the used tires locally from the scraped material suppliers. The specialist team found used tires of 20 brands in the plant yard that are presented in Table 1. The table shows that tires used in Bangladesh are imported from mostly South Asian and some of European countries.

Table 1. Tire brands found in Radiant Renewable Energy Ltd. pyrolysis plant yard

Sl. No.	Tire brands	Tire types	Country of origin	Sl. No.	Tire brands	Tire types	Country of origin
1.	Dunlop	Truck/bus and car	Japan	11.	Pioneer	Truck/bus and car	China
2.	Bridgestone	Truck/bus and car	Japan	12.	Kendoa Radial	Truck/bus and car	China
3.	Continental	Truck/bus and car	Great Britain	13.	GAJAH TUNGGAL	Truck/bus and car	Indonesia
4.	Goodyear	Truck/bus and car	South Africa	14.	MAXXIS	Truck/bus and car	Taiwan
5.	Courier	Truck/bus and car	Italy	15.	DEESTONE	Truck/bus and car	Thailand
6.	Michelin	Truck/bus and car	Italy	16.	Road star	Car	Bangladesh
7.	Eurotour	Truck/bus and car	Korea	17.	Gazi	Car	Bangladesh
8.	MRF	Truck/bus and car	India	18.	HT Super	Car	Bangladesh
9.	XPL	Truck/bus and car	India	19.	HT Army	Car	Bangladesh
10.	Birla	Truck/bus and car	India	20.	MUSAFIR	Autorickshaw	Bangladesh

3.2 Physical and chemical charateristics of solid tire wastes

The elemental and proximate analysis results and gross calorific values of the solid tire wastes from a servey of a quite number of international literature of more than 10 research groups [2 - 5, 8 - 9, 18 -19, 22 - 24, 35 - 38, 43 - 45] allover the world are presented in Table 2. From the information in the table, it can be seen that solid tire wastes contain very little moisture and a small amount of ash. The variation in the ash content is due to the variation in the inorganic material content of the tire rubber, including zinc, clay, and silica, as rubber additives. The relative magnitudes of these additives are greatly dependant on the rubber formulations and manufacturers. Higher presence of inorganic compounds in the solid tire wastes lowers their the GCV. One result of the high oxygen content is the relatively low lower heating value (LHV). The GCV for solid tire waste is 30 to 40 MJ/kg, compared to the GCV for hydrocarbon fuels of 40 to 44 MJ/kg. The GCV for tire waste is about twice that of woody biomass (19 to 20 MJ/kg). The volatile matter content of tire waste is comparatively high. A comparison with the typical values for bituminous coal shows similar carbon content, lower nitrogen and sulfur contents, higher hydrogen content, much higher volatile content, higher GCV, and lower moisture, ash and fixed-carbon content. These data indicate that tire waste is a potential source of energy and suitable for pyrolysis conversion.

Table 2. Elemental and proximate analysis, and GCVs of solid tire wastes

Analysis	Tire wastes generated allover the world	Bituminous Coals (India, Indonesia)	Bangladeshi coal (#Barapukuria)
Elemental analysis (wt %)			
C	85.00 – 88.50	60.00 – 75.00	64.41
H	6.50 – 8.00	3.75 – 6.00	3.96
N	0.30 – 0.50	1.00 – 1.22	1.32
O	1.00 – 3.50	7.30 – 12.00	7.29
S	0.80 – 1.90	0.50 – 3.00	0.52 – 0.60
Cl	Non-trace – 1.00	N/A	N/A
Ashes	Trace – 5.00	13.00 – 38.00	12.40
Proximate analysis (wt%)			
Moisture	0.80 – 1.70	5.00 – 9.50	10.00
Volatile fraction	57.00 – 70.00	20.00 – 30.00	29.20
Fixed carbon	22.00 – 35.00	30.00 – 50.00	48.40
Ashes	3.50 – 7.00	13.00 – 38.00	12.40
GCVs (MJ/kg)	28.00 – 40.00	28.00 – 32.00	25.68

#High volatile bituminous coal; Coal analysis presented here as received basis

4. Charateristics of pyrolysis products derived from solid tire wastes

4.1. Physical and chemical characteristics of the pyrolytic oil fractions

The pyrolytic liquids obtained from pyrolysis of selected tire wastes, which are oily organic compounds, appear dark-brown-color with a strong acrid smell. No phase separation was found to take place in the storage bottles. The physical and chemical properties of used tire derived pyrolysis liquids are presented in Table 3.

Details of the GC/MS analysis and lists of possible compounds identified in the tire derived pyrolysis liquids have been presented in the authors previous papers [35-38]. It was found that, tire pyrolysis liquids were very complex mixture from C_5-C_{20}, containing many aliphatic (42-65% peak area) and aromatic (5-18% peak area) compounds. The aliphatic compounds were mainly of alkane and alkene groups but the second was predominant in all of the four different tire-derived liquids. The aromatic compounds were only single ring alkyl aromatics. In addition to the main hydrocarbons, small percentage of nitrogen, sulphur, oxygen and chlorine containing compounds were also identified. The summery of identified compounds presented in the four different tire derived pyrolysis liquids are presented in Table 4.

Table 3. Charateristics of pyrolytic liquids in comparison to petroleum products

Analysis	Tire derived pyrolysis liquids	Typical fuel oil (furnace oil)	Commercial automotive No. 2 diesel
Elemental analysis (wt %)			
C	84.80 – 86.50	84.00	84.00 – 87.00
H	9.00 – 9.50	12.00	12.80 – 15.70
N	0.50 – 0.70	Trace	65 – 3000ppm
O	2.10 – 4.70	1.00	0.00
S	0.90 – 1.40	Up to 4.00	1100 – 7000ppm
Cl	90 – 270ppm	--	--
Ashes	0.10 – 0.31	Trace	0.00
Density (kg/m^3)	940 - 970	880 - 950	820 - 860
Viscosity (cSt)	4.60 – 4.90	--	2.00 – 4.50
Flash point (^{o}C)	≤32	66 – 93	>55
Pour point (^{o}C)	-3 to -5	18 – 72	-40 to -30
Moisture	N/A	≤1.00	≈80ppm
pH value	4.25 – 4.80	--	--
GCVs (MJ/kg)	40.80 – 42.90	43.00 – 45.00	44.00 – 46.00

TGA distillation test shows that more than 30 wt% of such oils is easily distillable fraction with boiling points between 70^{o}C and 210^{o}C, which is the boiling point range specified for commercial petrol. A typical boiling range for diesel oil is from 150 to 370^{o}C. The pyrolytic oil fraction corresponding to the 150 - 370^{o}C is about 60 wt% of the total oils. In order to establish the real potential use of such tire oil fraction as diesel oil, a more thorough characterisation of it, which should include cetane index, corrosive properties, flash point, etc., is needed. Fuel oil No. 1 is a light distillate which consists primarily of hydrocarbons in the C_9-C_{16} range; fuel oil No. 2 is a heavier distillate with hydrocarbons in the C_{11}-C_{20} range. Diesel fuels predominantly contain a mixture of C_{10} through C_{19} hydrocarbons, which include approximately 64% aliphatic hydrocarbons, l-2% olefinic hydrocarbons, and 35% aromatic hydrocarbons. Therefore, after filtration, centrifugation and desulphurization the pyrolytic liquids can be used directly as fuel oils or blended with diesel fuels for industrial furnaces, power plants and boilers.

4.2. Solid char fractions

The solid char fractions obtained at optimum reactor conditions were of equal size and shape as original tire pieces, which were easily disintegrable into black powder and steel cords. Elemental analysis of the pyrolytic char showed the results (by weight): C = 77.30-83.34%; H = 0.70-1.10%; N = 0.25-0.40%; S = 2.35-3.35% and O + ash = 13.36-18.15% [39]. Almost similar chemical compositions were found by the previous studies [46] while metallic elements Zn, Si, Ti, Al, Fe, Na, Ca, Pb and Mg in the ash were also indentified. The GCV of char fraction is 23.28-27.80 MJ/kg, which is compareable with that of the good quality coal. Pyrolytic char has potential as semireiforcing commercial carbon blacks for footwear and conveyor belts, as a carbon absorbent after proper activation, as a solid or slurry fuel etc. [2].

4.3. Gas fractions

The compositional analysis of gas fractions showed that tire derived pyrolysis gases are consisted of high concentrations of methane, ethane, propane, butene, butadiene and other hydrocarbons together with some CO, CO_2, H_2, SO_2, H_2S, NH_3 and N_2 . The GCV of the pyrolysis gases is 37.85 - 40.72 MJ/m^3, which is very close to that of natural gas (about 39 MJ/m^3 at NTP) and hence it would be sufficient to provide the heat energy required by the pyrolysis process. More or less similar gas compositions are also obtained by Rodriguez et al. [2] with better GCV of 75.50 MJ/m^3 or 42.1 MJ/kg. The former research group [47] also found the GCV of tire derived pyrolytic gas 35-40 MJ/kg and reported that this value is sufficient to heat pyrolysis reactor.

Table 4. Summery of identified compounds in the four different tire-derived pyrolysis liquids

Compounds identified	Total concentrations (% peak area)			
	B/RT liquid	MT liquid	PCT liquid	TT liquid
Aliphatic	42.22	49.54	43.04	65.75
Aromatic	16.14	17.23	29.15	4.12
Nitrogenated	7.51 ($C_{11}H_{13}NOS$; $C_9H_{13}NO_2$)	4.25 ($C_{11}H_{13}NOS$; $C_7H_7N_3$)	0.67 ($C_{10}H_{11}NO_2$)	0.69 ($C_{11}H_{13}NOS$; C_2H_5N)
Sulphurated	5.04 ($C_{11}H_{13}NOS$)	0.80 ($C_{11}H_{13}NOS$)	0.34 ($C_{11}H_{12}O_2S$)	0.56 ($C_{11}H_{13}NOS$)
Oxygenated	9.82 ($C_{10}H_{16}O$; $C_{11}H_{13}NOS$; $C_{19}H_{30}O_2$ +…)	2.16 ($C_{11}H_{13}NOS$; C_6H_5ClO; $C_8H_{15}ClO$ +…)	2.85 ($C_{19}H_{30}O_2$; $C_{10}H_{11}NO_2$; $C_{11}H_{12}O_2S$)	1.57 ($C_{10}H_{16}O$; $C_{11}H_{13}NOS$; $C_{19}H_{30}O_2$ +…)
Chlorinated	1.82 ($C_{12}H_{25}Cl$; $C_{14}H_{29}Cl$)	1.58 (C_6H_5ClO; $C_8H_{15}ClO$; $C_{12}H_{25}Cl$)	0.95 ($C_7H_{14}Cl_2$)	2.45 ($C_{12}H_{25}Cl$; $C_{16}H_{33}Cl$)
Limonene	10.95	29.54	11.11	50.86

5. Conclusions and recommendations

The fuel properties of the tire derived pyrolysis liquids including density, viscosity, GCV, carbon and hydrogen contents are found almost comparable to those of the commercial diesel fuels but higher sulphur content and lower flash point are problematic. The liquid may be used as diesel fuel or heating oils after the upgrading such as desulphurization and dehydrogenation or blending them with petroleum refinery streams. The pyrolytic liquids abundantly contain olefins, especially limonene and light aromatics; whose have higher market values as chemical feedstock than their use as fuels. The pH value of the pyrolytic liquids is 4~5, which is in weak acidic nature. It is found that there is very little contamination of the liquids with metals (V, Mn, Mg, Ba, Ni, Ti, Cu, Cr, Cd, Co, Fe, Al, and Zn), and does not contaminate with glass and PET plastic and/or other plastics. Thus, storage and handling of the liquids are little problematic in industrial usage in this regard.

Now Bangladesh is suffering from strong liquid petroleum crisis and the price of furnace oil is about 60 TK/ litre. Several number of furnace oil based new power plants have been ideal due to lack of oil supply. Besides, a lot of steam boilers used in garmens factories and other industries are using furnace oil. It is estimated that the production cost of pyrolysis oil is 30 TK/litre that is much lower than the present furnace oil price in Bangladesh. Thus, at this crucial moment of the country's liquid fuel, it is undoubtly a noble initiative of RRE Ldt. for production of alternative diesel from scrap tires. A total of 7 pyrolysis plants of capacity 720 tons/month may be established for annual tire waste generation (64000 metric tons) in the country. If it would be pyrolysed all of tire wastes in the country, the import bills will reduce for 29400 tons (205000 barrels) of oils, 6400 tons of steel and 22400 tons of coal every year. Moreover, a big amount of hazardous solid waste like used tires would be managed properly; the dependence on imported petroleum crude oils and unemployment problem of Bangladesh would be reduced as well.

Pyrolysis of used tire is a concern of waste material with a reasonable amount of sulfur and trace amount of other objectionable elements and hence its conversion into enegry sholud be considered very carefully. Tire waste pyrolysis plant at RRE Ltd. is small and hence the concentration of emission surrounding the plant compound is possibly lower than standard prescrition values. However, the following recommended pionts should be followed for better operation and further extension of the plant, and also for our sincere corner to safe environment:

(i) Solid tire wastes should be cleaned properly before loading into the reactor to maintain the quality of the product liquids as well as to reduce emissioms from the plant.

(ii) The excess gasious product should not be released into the atmosphere. It may be stored in a container to burn in the furnace from the beginning of firing or may be supplied to the local people for coocking.

(iii) Handling and transpotation of the product liquid and char should be in a closed conduit/system to reduce fugitive

VOC and PM emissions, respectively.

(iv) To ensure environment friendly production of alternative diesel from tire wastes, demister filters and wet-scrubber with CaOH/NaOH column should be incorporate properly, and their operation must be monitored carefully.

(v) The standard design of the chimney must be followed to exhaust flue gas in a safe layer of atmosphere.

(vi) Wastewater generated in the plant must be treated and disposed sincerely.

(vii) Mountings should be inspected regularly and replace them by wright one while require for safer running of the plant.

(viii) To make the technology sustainable, upgrading of liquid product and better utilization of char are very important.

(ix) Some of the operators employed in the pyrolysis plant need to be skilled in the relavent field.

(x) Sulfur and clorine content of solid tire wastes should be checked twice a year for controling SOx and dioxin emissions from the plant as well as sulfur and clorine containing compounds in the liquid and char products.

(xi) The plant is installed/situated in a populated area and hence its furteher extension in the present location should not be considered.

(xii) Finally, it may be concluded that the plant can be run only under continuous monitoring and consultancy support of a tire pyrolysis specialist team because of new technology and waste material concern.

References

[1] Bangladesh Bureau of Statistics, Government of Peoples Republic of Bangladesh. Statistical Year Book of Bangladesh 2008. 28^{th} ed.; Dhaka, 2009.

[2] Rodriguez IM, Laresgoiti MF, Cabrero MA, Torres A, Chomon MJ, Caballero B. Pyrolysis of scrap tires. Fuel Processing Technology 2001;72:9–22. [and references therein]

[3] Laresgoiti MF, Caballero BM, De Marco I, Torres A, Cabrero MA and Chomon MJJ. Characterization of the liquid products obtained in tire pyrolysis. J. Anal. Appl. Pyrolysis 2004;71:917–934.

[4] Gonzalez JF, Encinar JM, Canito JL, Rodriguez JJ. Pyrolysis of automotive tire waste. Influence of operating variables and kinetic study. J. Anal. Appl. Pyrolysis 2001;58–59:667–83 [and references therein].

[5] Diez C, Martinez O, Calvo LF, Cara J, Moran A. Pyrolysis of tires. Influence of the final temperature of the process on emissions and the calorific value of the products recovered. Waste Management 2004;24:463-469.

[6] Dai X, Yin X, Wu C, Zhang W, Chen Y. Pyrolysis of waste tires in a circulating fluidized-bed reactor. Energy 2001;26:385-399.

[7] Pakdel H, Pantea DM, Roy C. Production of dl-limonene by vacuum pyrolysis of used tires. J. Anal. Appl. Pyrolysis 2001;57:91–107.

[8] Cunliffe AM, Williams PT. Composition of oils derived from the batch pyrolysis of tires. J. Anal. Appl. Pyrolysis 1998;44:131–52. [and references therein]

[9] Roy C, Chaala A, Darmstadt H. Vacuum pyrolysis of used tires End-used for oil and carbon black products. J. Anal. Appl. Pyrolysis 1999;51:201–221.

[10] Barbooti MM, Mohamed TJ, Hussain AA, Abas FO. Optimization of pyrolysis conditions of scrap tires under inert gas atmosphere. J. Anal. Appl. Pyrolysis 2004;72:165–170.

[11] Williams PT, Brindle AJ. Aromatic chemicals from the catalytic pyrolysis of scrap tires. J. Anal. Appl. Pyrolysis 2003;67:143–164.

[12] Williams PT, Brindle AJ. Temperature selective condensation of tyre pyrolysis oils to maximise the recovery of single ring aromatic compounds. Fuel 2003;82:1023–1031.

[13] Pakdel H, Roy C, Aubin H, Jean G, Coulombe S. Formation of limonene in used tire vacuum pyrolysis oils. Environ. Sci. Technology 1992;9:1646.

[14] Cunliffe AM, Williams PT. Influence of process conditions on the rate of activation of chars derived from pyrolysis of used tires. Energy & Fuels 1999;13(1):166–175.

[15] Zabaniotou AA, Stavropoulos G. Pyrolysis of used automotive tires and residual char utilization. J. Anal. Appl. Pyrolysis 2003;70:711–722.

[16] Zabaniotou AA, Madau P, Oudenne PD, Jung GC, Delplancke MP, Fontana A. Active carbon production from used tire in two-stage procedure: industrial pyrolysis and bench scale activation with H_2O-CO_2 mixture. J. Anal. Appl. Pyrolysis 2004;72:289–297.

[17] Murena F, Garufi E, Smith RB, Gioia F. Hydrogenative pyrolysis of waste tires. Journal of Hazardous Materials 1996;50:79-98.

[18] Ucar S, Karagoz S, Ozkan AR, Yanik J. Evaluation of two different scrap tires as hydrocarbon source by pyrolysis. Fuel 2005;84:1884-1892.

[19] Kyari M, Cunliffe A, Williams PT. Characterization of oil, gas and char in relation to the pyrolysis of different brands of scrap automotive tires. Energy & Fuel 2005;19:1165-1173.

[20] Laresgoiti MF, De Marco I, Torres A, Caballero B, Cabrero MA and Chomon MJ. Chromatographic analysis of the gases obtained in tyre pyrolysis. J. Anal. Appl. Pyrolysis 2000;55:43–54.

[21] Merchant AA, Petrich MA. Pyrolysis of scrap tires and conversion of chars to activated carbon. AIChe J. 1993;39:1370–1376.

[22] Williams PT, Besler S, Taylor DT. The pyrolysis of scrap automotive tires: The influence of temperature and heating rate on product composition. Fuel 1990;69:1474-1482.

[23] Napoli A, Soudais Y, Lecomte D, Castillo S. Scrap tyre pyrolysis: Are the effluents valuable products? J. Anal. Appl. Pyrolysis 1997;40-41:373-382.

[24] Morillo R, Aylon E, Navarro MV, Callen MS, Aranda A, Mastral AM. The application of thermal processes to valorize waste tire. Fuel processing Technology 2006;87:143-147.

[25] Mastral AM, Murillo R, Callen MS, Garcia T, Snape CE. Influence of process variables on oils from tire pyrolysis and hydropyrolysis in a swept fixed bed reactor. Energy & Fuels 2000;14(4):739-744.

[26] Chang YM. On pyrolysis of waste tire: Degradation rate and product yields. Resour. Conserv. Recy. 1996;17:125-139.

[27] Zailani RB. Fluidized-bed pyrolysis of organic solid waste, M.Sc. Engg. Thesis, Universiti Teknologi Malaysia, Malaysia, 1995.

[28] Islam MN, Islam MN, Beg MRA. Fixed bed pyrolysis of scrap tyre for liquid fuel production. International Energy Journal 2004;5(1):11-18.

[29] Kaminsky W, Mennerich C. Pyrolysis of synthetic tire rubber in a fluidised-bed reactor to yield 1,3-butadiene, styrene and carbon black. J. Anal. Appl. Pyrolysis 2001;58-59:803-811.

[30] Mirmiran S, Pakdel H, Roy C. Characterization of used tire vacuum pyrolysis oil: Nitrogenous compounds from the naphtha fraction. J. Anal. Appl. Pyrolysis 1992;22:205-215.

[31] Roy C, Rastegar A, Kaliaguine S, Darmstadt H. Darmstadt, Physicochemical properties of carbon blacks from vacuum pyrolysis of used tires. Plast. Rubber Compos. Proc. Appl. 1995;23:21-30.

[32] Aguado R, Olazar M, Arabiourrutia M, Alvarez S, Bilbao J. In: Proceedings of the VIII Congreso de Ingenier and Ambiental PROMA'03, Bilbao, Spain, 2003.

[33] Islam, M. R., Parveen, M., and Haniu, H. Properties of sugarcane waste-derived bio-oils obtained by fixed-bed fire-tube heating pyrolysis. Bioresource Technology, Vol. 101, No. 11; pp. 4162-4168; June 2010.

[34] Islam, M.R., Parveen, M., HANIU, H and Sharker, M. R. Innovation in pyrolysis technology for management of scrap tire: a solution of Energy and Environment. International Journal of Environmental Science and Development, Vol. 1; No.: 1; pp. 89-96; April 2010.

[35] Islam, M. R, Kim, S. I., Haniu H. and Beg, M. R. A. Fire-tube heating pyrolysis of car tire wastes: end uses of product liquids as fuels and chemicals. International Energy Journal, Vol. 9, No. 3; pp: 189-198; September 2008.

[36] Islam, M. R., Haniu, H. and Beg, M. R. A. Liquid fuels and chemicals from pyrolysis of motorcycle tire waste: product yields, compositions and related properties. FUEL, Vol. 87, No. 13-14; pp. 3112-3122; October 2008.

[37] Islam, M. R., Tushar, M. S. H. K. and Haniu, H. Production of liquid fuels and chemicals from pyrolysis of Bangladeshi bicycle/rickshaw tire wastes. Journal of Analytical and Applied Pyrolysys, Vol. 82, No. 1; pp. 96-109; May 2008.

[38] Islam, M. R., Haniu, H. and Beg, M. R. A. Limonene-rich liquids from pyrolysis of heavy automotive tire wastes. Journal of Environment and Engineering, Vol. 2, No. 4; pp. 681-695; October 2007.

[39] Islam, M. R., Joardder, M. U. H., Hasan, S. M., Takai, K. and Haniu, H. Feasibility study for thermal treatment of solid tire wastes in Bangladesh by using pyrolysis technology. Waste Management, Vol. 31; pp. 2142-2149; 2011.

[40] Islam, M. R. Fixed-bed fire-tube heating pyrolysis of solid tire wastes available in Bangladesh for production of alternative liquid fuels and valuable chemicals. PhD Thesis, Department of Mechanical Engineering, National University Corporation Kitami Institute of Technology, Hokkaido, Japan; 2008 (and references therein).

[41] Sharma, V. K., Mincarini, M., Fortuna, F., Cognini, F. and Cornacchia, G. Disposal of waste tires for energy recovery and safe environment – review. Energy Conv. and Manag., Vol. 39, No. 5/6; pp. 511-528; 1998.

[42] Islam, M. R., Haniu, H., Fardoushi, J. Pyrolysis kinetics behaviour of solid tire wastes available in Bangladesh. Waste Management, Vol. 29; pp. 668-677; 2009.

[43] Galvagno, S., Casu, S., Casabianca, T., Calabrese, A., Cornacchia, G. Pyrolysis process for treatment of scrap tires: preliminary experimental results. Waste Management, Vol. 22, pp. 917-923; 2002.

[44] Berrueco C, Esperanza E, Mastral FJ, Ceamanos J, Garcia-Bacaicoa P. Pyrolysis of waste tyres in an atmospheric static-bed batch reactor: Analysis of the gases obtained. J. Anal. Appl. Pyrolysis 2005;74:245–253.

[45] Qu, W., Zhou, Q., Wang, Y., Zhang, J., Lan, W., Wu, Y., Yang, J., Wang, D. Pyrolysis of tire waste on ZSM-5 zeolite with enhanced catalytic activities. Polymer Degradation and Stability, Vol. 91; pp 2389-95; 2006.

[46] Helleur B, Popovic N, Ikura M, Liu D. Characterization and potential applications of pyrolytic char from ablative pyrolysis of used tires. 14th International Symposium on Analytical and Applied Pyrolysis, April 2–6, Sevilla-Spain, J. Anal. Appl. Pyrolysis, Vol. 58–59; pp. 813–824; 2001.

[47] Roy, C. and Unsworth, J. Pilot-scale plant demostration of used tyres vacumm pyrolysis. In Pyrolysis and gasification; Ferrero, G. L., Maniatis, K., Buekens, A., Eds.; Elsevier Applied Science: London, U. K., 1989.

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Effect of coconut biodiesel blended fuels on engine performance and emission characteristics

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Abstract

Alternative fuels have received much attention due to the depletion of world petroleum reserves and increased environmental concerns. Thus processed form of vegetable oil (Biodiesel) offers attractive alternative fuels to compression ignition engines. The present work investigates the engine performance parameters and emissions characteristics for direct injection diesel engine using coconut biodiesel blends without any engine modifications. A total of three fuel samples, such as DF (100% diesel fuel), CB5 (5% coconut biodiesel and 95% DF), and CB15 (15% CB and 85% DF) respectively are used. Engine performance test has been carried out at 100% load, keeping throttle 100% wide open with variable speeds of 1500 to 2400 rpm at an interval of 100 rpm. Whereas, engine emission tests have been carried out at 2200 rpm at 100% and 80% throttle position. As results of investigations, there has been a decrease in torque and brake power, while increase in specific fuel consumption has been observed for biodiesel blended fuels over the entire speed range compared to net diesel fuel. In case of engine exhaust gas emissions, lower HC, CO and, higher CO_2 and NO_x emissions have been found for biodiesel blended fuels compared to diesel fuel. Moreover, reduction in sound level for both biodiesel blended fuels has been observed when compared to diesel fuel. Therefore, it can be concluded that CB5 and CB15 can be used in diesel engines without any engine modifications and have beneficial effects both in terms of emission reductions and alternative petroleum diesel fuel.

Keywords: engine performance, emission, coconut biodiesel, sound level.

1. Introduction

The fossil fuel demand is continuously increasing world over resulting in rapid depletion of fossil fuel deposits [1]. According to the US department of energy, the world’s oil supply will reach its maximum production and midpoint of depletion sometime around the year 2020 [2]. In several studies, it has been experimentally investigated that the human health hazards are associated with exposure to diesel exhaust emissions [3-6]. Therefore, limited fossil fuels and intensified environment pollution, it has become a global issue to develop such clean fuel, which is technically feasible, domestically available and environmentally acceptable [7]. Generally, recommended biodiesel for use as a substitute for petroleum-based diesel is produced from vegetable oil or animal fats by transesterification process. Biodiesel is an oxygenated, renewable, biodegradable and environmentally friendly bio-fuel with low emission profile [8]. According to experimental results

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conducted by various researchers around the world, it has been reported that biodiesel fuelled engine produced marginal loss in engine torque and power, and increase in bsfc as compared to diesel fuel. Besides that, it reduces the emissions of carbon monoxide (CO), hydrocarbon (HC), sulfur dioxide (SO_2), polycyclic aromatic hydrocarbons (PAH), nitric polycyclic aromatic hydrocarbons (nPAH) and particulate matter (PM). However, a majority of research results have indicated an increase in nitrogen oxides (NOx) [9-13, 7].

According to the study [12] conducted on a six cylinders direct injection diesel engine, it has been reported that the increase of biodiesel percentage in the blend involves a slight decrease of both power and torque over the entire speed range. In particular, with pure biodiesel there was a reduction by about 3% maximum power and about 5% of maximum torque. Moreover, with pure biodiesel, the maximum torque was found to have reached at higher engine speed. Similar results were investigated by Aydin and Bayindir [14] using cottonseed oil methyl ester (CSOME). However, a decrease of CO, NO_x and SO_2 emissions were observed in the same study. In another study [15], similar power and torque output with higher bsfc were recorded using waste cooking biodiesel when compare to diesel fuel, whereas in terms of exhaust emissions, lower CO and HC emissions were reported.

The main purpose of the present study is to determine the suitability of using CB5 and CB15 on CI engine without any major hardware modification and to compare the results of these blend fuels with diesel fuel in terms of engine performance, exhaust emission and sound level.

2. Experimental methods and materials

In this study, a one-cylinder, four-stroke diesel engine is selected and is mounted on a test-bed. Its major specifications are given in Table 1. The experimental setup with necessary instrumentation has been shown in Fig. 1. In order to supply the fuel to the test engine, two fuel tanks, one for diesel fuel and another for blend fuels were used. The engine is coupled to an eddy current dynamometer. It can be operated at a maximum power of 20 kW at 2450 to 10000 rpm. The essential fuel properties can be found in Table 2. The engine was initially fuelled with diesel fuel to provide the baseline data and then, it was fuelled with biodiesel blend fuels. Before stopping the test engine after each test with biodiesel blend fuels, the engine was switched on diesel fuel until all the biodiesel based blend is purged from the fuel lines, injection pump and injector to avoid clogging when the engine is cooling down.

The performance test was carried out at 100% load keeping throttle 100% wide open using Dynomax-2000 software. The test procedure was carried out through DYNOMAX 2000 data control system. Engine performance data were measured at “Step RPM Test” mode (between 1500 and 2400 rpm with intervals of 100 rpm). The emissions of different pollutants were measured at 2200 rpm at 100% and 80% throttle position. A portable BOSCH exhaust gas analyzer (model ETT 0.08.36) was used to measure the hydrocarbon (HC) in part per million (ppm) whereas, carbon monoxide (CO) and carbon dioxide (CO_2) were measured in percentage volume (%vol). NO_x emission was measured using AVL 4000 (Make: Graz/Austria) gas analyzer. In order to measure the sound level at different loads, the measurements of engine noise were taken from five directions at 1 meter away from the test engine bed such as front, rear, left, right and top side. However, in this work, only front side was selected, which produced the highest level of the noise. In this regard, to measure the noise level, NI Sound Level Measurement System was adopted. Therefore, PCB 130 Series of Array Microphones (microphone model 130D20) was employed in this work.

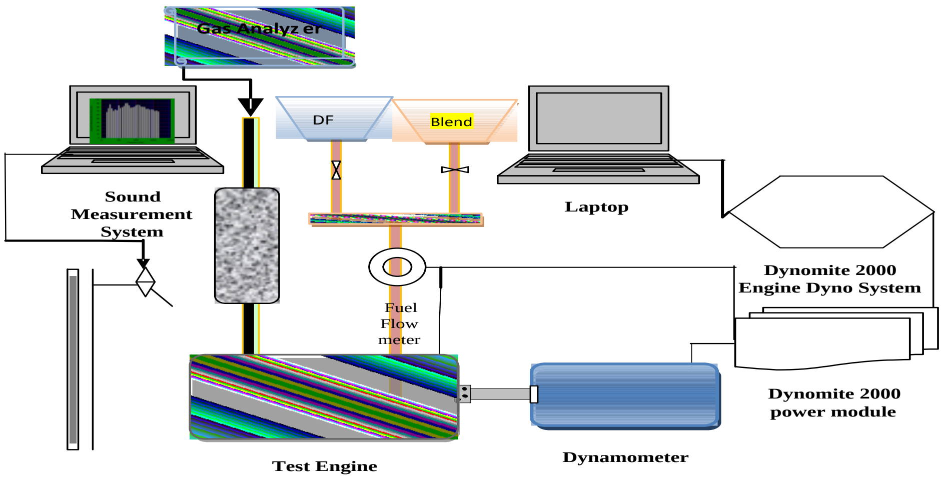

Fig. 1. Schematic diagram of experimental setup.

Table 1. Test engine technical specifications

Engine type		Four stroke DI diesel engine
Number of cylinders		One
Aspiration		Natural aspiration
Cylinder bore x stroke	mm	92 x 96
Displacement	L	0.638
Compression ratio		17.7
Max. engine speed	rpm	2400
Max. power	kW	7.7
Injection timing	deg.	bTDC 17.0
Injection pressure	kg/cm^2	200

Table 2. Some of the important tested fuel properties

Parameters	CB5	CB15	DF
Kinematic viscosity @ 40 ^{0}C (cSt)	3.344	3.425	3.317
Heating value (MJ/kg)	45.407	44.838	45.547
Density @ 40 ^{0}C (gm/cm3)	0.823	0.825	0.822
Flash point (^{0}C)	83	86	78
Cetane number	51.5	53.4	51

3. Results and discussions

3.1. Engine performance analysis

3.1.1. Torque

Fig. 2(a) presents the effects of coconut biodiesel addition (% by volume) and net diesel fuel on the engine torque with respect to the engine speed. Keeping in view the engine torque results with biodiesel blends, it can be observed that the trend of this parameter as a function of speed for both biodiesel blends is almost found to be similar to net diesel fuel. Initially, engine torque increases as the engine speed increases until it reaches a maximum value and then starts decreases with further increasing engine speed. The engine torque reduction after certain speed is found to be due to the two main factors. Firstly, it is the lowered volumetric efficiency of the engine due to the increase in the corresponding engine speed, and the second one is the augmentations in the mechanical losses [16]. For both biodiesel blends and diesel fuel, the maximum torque values were found at 2200 rpm of engine. However, net diesel fuel shows some higher torque values than biodiesel blends due to the fact that diesel fuel has higher heating value than biodiesel blends. The average torque reduction compared to net diesel fuel is found as 0.69% for CB5 and 2.58% for CB15 respectively.

3.1.2. Brake power

Fig. 2(b) illustrates the variations in the brake power for net diesel fuel and biodiesel blends as a function of the engine speed. It can be observed that brake power of the engine increases with increasing engine speed until 2200 rpm and then starts to decrease due to the effect of higher frictional force. The engine brake power for biodiesel blends was found to be lower than obtained for net diesel fuel. The lower brake power for CB5 and CB15 can be due to their respective lower heating values. The average power reduction compared to diesel fuel over the entire speed range is found as 0.66% for CB5 and 2.61% for CB10% respectively.

3.1.3. Brake specific fuel consumption

Fig. 2(c) presents the brake specific fuel consumption (bsfc) for net diesel fuel and biodiesel blends as a function of engine speed. Good engine performance in terms of fuel economy is reflected by the bsfc parameter. For the biodiesel blends, heating value is found slightly higher than that for diesel fuel. This may be attributed to the lower heating value and higher density of the blends. It is also known that biodiesel contains oxygen content, which results in the lower heating value [17]. Thus for the same energy output from the engine, it requires larger mass fuel flow, which increases bsfc to compensate the reduced chemical energy in the fuel [18,19]. The average increase in bsfc compared to diesel fuel is found as 0.53% for CB5 and 2.11% for CB15 respectively.

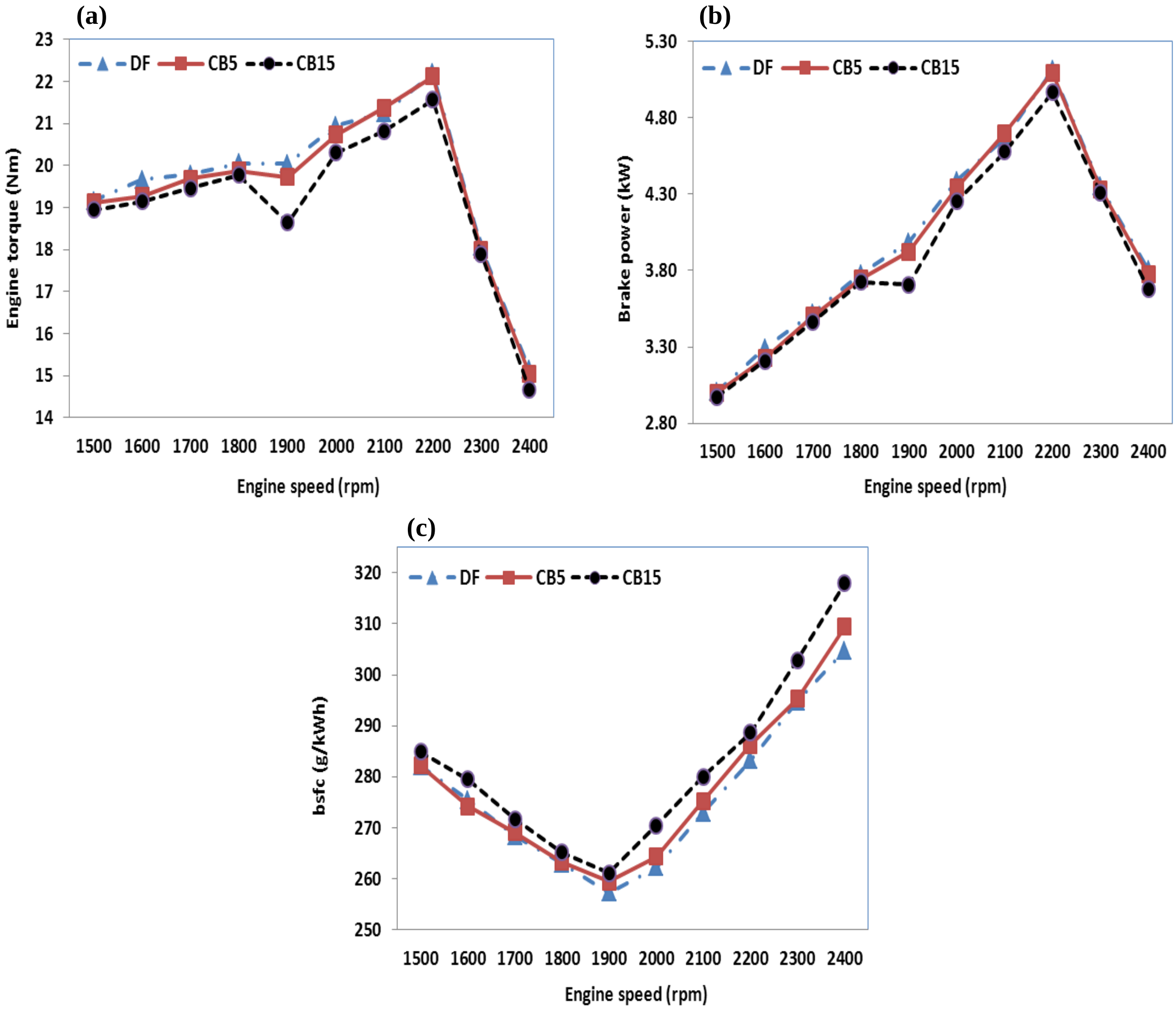

Fig. 2. Engine performance analysis.

3.2. Exhaust emission analysis

3.2.1. Exhaust gas temperature

Fig. 3(a) presents exhaust gas temperature at 2200 rpm at 100% and 80% throttle position for diesel fuel and biodiesel blends. In order to indicate the cylinder combustion temperature, engine exhaust temperature has been considered as one of the important parameters. Therefore, it is a good parameter in analyzing the exhaust emissions especially for NO_x. The increase in exhaust gas temperature compared to diesel fuel at 2200 rpm and at 100% throttle position was observed as 2.22% for CB5 and 3.33% for CB15 whereas, at 80% throttle position, increase was found as 3.62 for CB5 and 5.96% for CB15 respectively.

3.2.2. Carbon monoxide (CO) emission

CO emissions at 2200 rpm, at 100% and 80% throttle position are presented in Fig. 3(b). CO is one of the compounds formed during the intermediate stages of fuels and is formed mainly due to incomplete combustion of fuels. If combustion proceeds to completion, CO is converted to CO_2. If the combustion is incomplete due to shortage of air or low gas temperature, CO will be formed. In case of biodiesel blends, CO emissions were lower than that of diesel fuel, due to some extra oxygen contents, which convert CO to CO_2 and resulted in complete combustion of the fuel [20]. In another study, it has been reported that higher cetane munber of biodiesel blends; results in the lower possibility of formation of rich fuel zone and thus reduces CO emissions [21]. Average reduction in CO at 2200 rpm and 100% throttle position was found as; 13.38% for CB5 and 21.51% for CB15, whereas, at 80% throttle position, reduction in CO was found as 5.98% for CB5 and 16.03% for CB15 respectively.

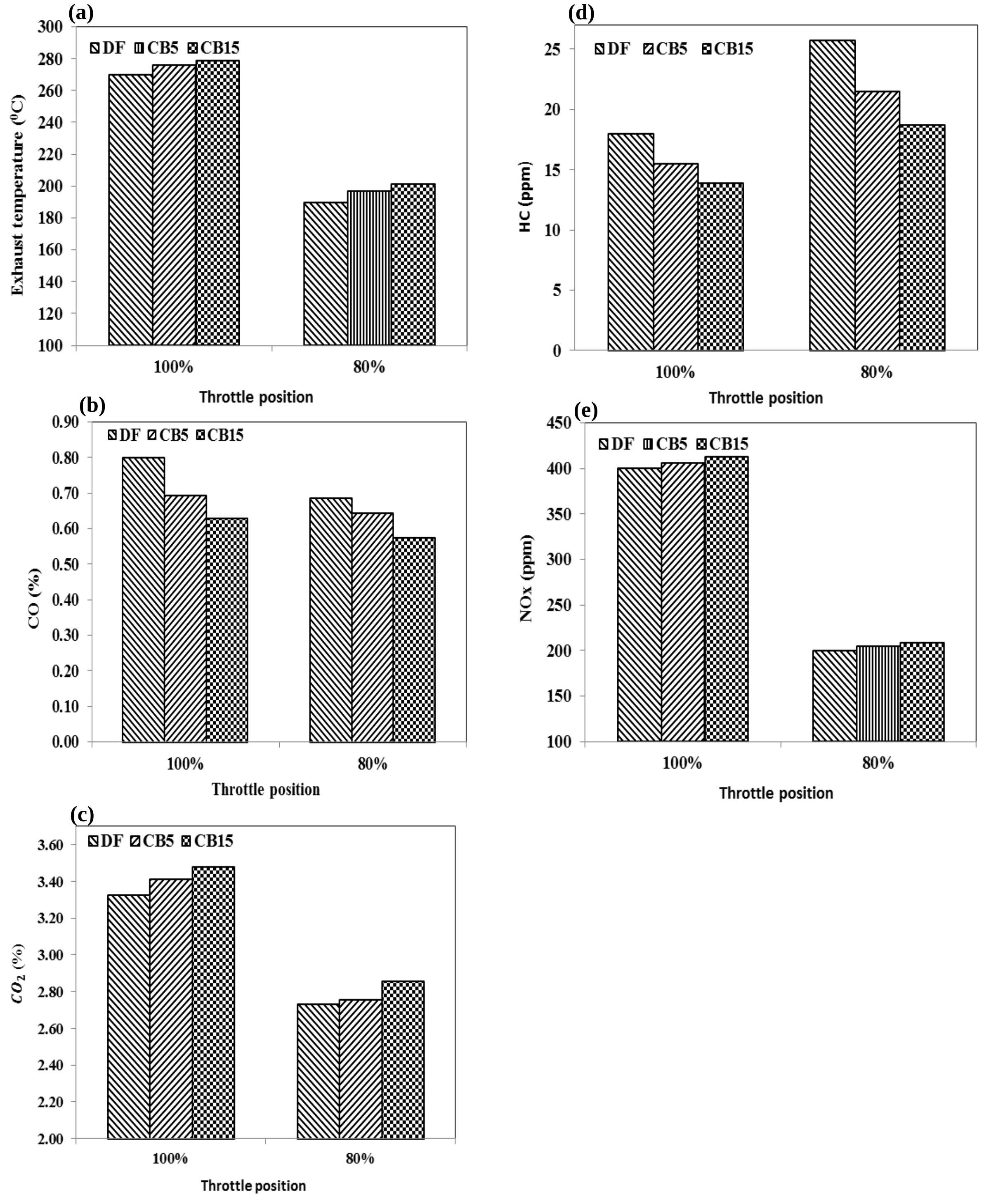

Fig. 3. Engine exhaust emission analysis.

3.2.3. Carbon dioxide (CO_2) emission

Fig. 3(c) illustrates the carbon dioxide (CO_2) emissions for diesel fuel and biodiesel blends at 2200 rpm at 100% and 80% throttle position. It can be noted that the CO_2 emissions for biodiesel blends increased compared to diesel fuel. This may be attributed to the oxygen content in biodiesel which reacts with unburned carbon atoms during the combustion and increases the formation of CO_2. More amount of CO_2 in exhaust emission indicates the complete combustion of fuel [22]. Compared to diesel fuel, CO_2 for biodiesel blends at 2200 rpm and at 100% throttle position, was increased as 2.54% for CB5 and 4.64% for CB15 respectively. Whereas, at 2200 rpm at 80% throttle position, CO_2 compared to diesel fuel was increased as 0.79% and 4.56% respectively.

3.2.4. Hydrocarbon (HC) Emission

HC emissions for diesel fuel and biodiesel blends at 2200 rpm at 100% and 80% throttle position are shown in Fig. 3(d). it has been reported that the oxygenated compounds available in the blends improve the fuel oxidation and thus it reduces HC emissions [23]. When the oxygen content of fuel blend is increased, it requires less oxygen for combustion. However, oxygen content of fuel is the main reason for more complete combustion and HC emission reduction. Furthermore, higher cetane number of biodiesel blends reduces the combustion delay, and such a reduction has also been related to decreases in HC emissions [24-26]. Compared to diesel fuel, reduction in HC at 2200 rpm and 100% throttle position was found as 13.89% for CB5 and 22.88% for CB15 respectively, whereas, at 80% throttle position, HC emission reduction was found as 16.58% CB5 and 27.19% for CB15 respectively.

3.2.5. Nitrogen oxide (NO_x) emission

Fig. 3(e) presents NO_x emissions at 2200 rpm at 100% and 80% throttle position for diesel fuel and biodiesel blends. The NO_x emissions for blends are found higher than diesel fuel. It has been reported that formation of NOx emissions are strongly dependent upon the equivalence ratio, oxygen concentration and burned gas temperature. According to Beatrice et al. [27] and Song et al. [28] increased oxygen levels increase the maximum temperature during the combustion, and thus increase NOx formation. It is also agreed that in the production of NO_x, the fuel borne oxygen is more effective than the external oxygen supplied with the air [14]. The increase in NO_x compared to diesel fuel at 2200 rpm and at 100% throttle position was observed as 1.42% for CB5 and 3.19% for CB15 whereas, at 80% throttle position, increase was found as 2.44 for CB5 and 4.64% for CB15 respectively.

3. Noise Emission

As noise effects are restricted to the time of its emission, therefore, noise emission is thought to be quite different from that of air pollutants or other climate gases [29]. The diesel engine produces much more noise than that produced by the spark ignition engine [30]. The combustion noise is associated with the maximum pressure rise rate produced in the cylinder. Thus, higher pressure rise rate produces higher combustion noise and vice versa. It has been found that reduction in the ignition delay period results in reduction of the maximum pressure rise rate ($dp/d\Theta$), which leads to the smoother engine running [31]. Thus shorter ignition delay reports for biodiesel and blends have been investigated by many authors [32-34]. In our research work, sound level for diesel fuel and biodiesel blends was measured form five different directions (front, rear, left, right and top) around the test engine bed. However in this study as shown in Fig. 3, only front side has been selected which produced the highest level of the noise. Fig. 3 shows that the sound level for CB5 and CB15 is decreased as compared to diesel fuel and increased as the load (bmep) increased for each fuel sample. Lower sound level for biodiesel blends compared to diesel fuel may be attributed due to their higher viscosities which produced lubricity and damping and thus resulted in decrease of sound level. Secondly, higher cetane number of blend fuels may decrease the ignition delay which causes the maximum pressure rise rate to decrease so the engine produced lower sound level. Besides that, it was noted that engine noise emissions were reduced with the increase in fuel oxygen content in blend fuels due to improved combustion efficiency.

4. Conclusion

This work presented the experimental investigations in terms of engine performance and emissions of using diesel fuel as baseline and biodiesel blends such as CB5 and CB15 respectively. The experimental results of this research work can be summarized as follows.

Compared to diesel fuel, engine torque and brake power for biodiesel blends were decreased, mainly due to their respective lower heating values. The bsfc values for biodiesel blends were higher when compared to diesel fuel due to lower heating values and higher densities.

In case of engine exhaust gas emissions, HC and CO emissions were reduced whereas, CO_2 and NO_x emissions were increased for CB5 and CB15 when compared to diesel fuel at both engine operating conditions.

In comparison with the diesel fuel, biodiesel blends produced lower sound levels due to many factors including increase in oxygen content, reduction in the ignition delay, higher viscosity, lubricity etc.

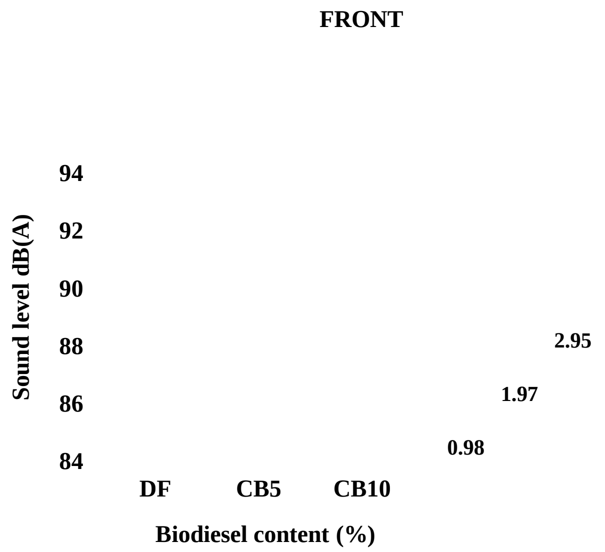

Fig. 4. Sound level at various loads for diesel fuel and biodiesel blends.

Acknowledgements

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References

[1] Tesfa B, Mishra R, Gu, F, Ball AD. Water injection effects on the performance and emission characteristics of a CI engine operating with biodiesel. Renewable Energy 2012;37:333-344.
[2] Jindal S, Nandwana BP, Rathore NS, Vashistha V. Experimental investigation of the effect of compression ratio and injection pressure in a direct injection diesel engine running on Jatropha methyl ester. Applied Thermal Engineering 2010; 30: 442–448.
[3] Törnqvist M, Ehrenberg L. On cancer risk estimation of urban air pollution. Environmental health perspectives 1994;102(Suppl 4):173.
[4] Iwai K, Adachi S, Takahashi M, Möller L, Udagawa T, Mizuno S, Sugawara I. Early Oxidative DNA Damages and Late Development of Lung Cancer in Diesel Exhaust-Exposed Rats. Environmental Research 2000;84(3):255-264.
[5] Dybdahl M, Risom L, Bornholdt J, Autrup H, Loft S, Wallin H. Inflammatory and genotoxic effects of diesel particles in vitro and in vivo. Mutation Research/Genetic Toxicology and Environmental Mutagenesis. 2004;562(1-2):119-131.
[6] Vincent R. Acute Cardiovascular Effects in Rats from Exposure to Urban Ambient Particles, STATEMENT: Synopsis of Research Report 104. Safe Environments Programme, EPA Grant Number: R828112C104, Environmental Protection Agency, 2003.
[7] Liaquat AM, Kalam MA, Masjuki HH, Jayed MH. Potential emissions reduction in road transport sector using biofuel in developing countries. Atmospheric Environment 2010;44(32):3869-3877.
[8] Hirkude JB, Padalkar AS. Performance and emission analysis of a compression ignition Engine operated on waste fried oil methyl esters. Applied Energy 2012;90: 68－72.

[9] Behçet R. Performance and emission study of waste anchovy fish biodiesel in a diesel engine. Fuel Processing Technology 2011; 92:1187-1194.
[10] Aydin H, İlkılıç C. Effect of ethanol blending with biodiesel on engine performance and exhaust emissions in a CI engine. Applied Thermal Engineering 2010;30:1199-1204.
[11] Machado Corrêa S, Arbilla G. Carbonyl emissions in diesel and biodiesel exhaust, Atmospheric Environment 2008;42:769-775.
[12] Carraretto C, Macor A, Mirandola A, Stoppato A., Tonon S. 2011Biodiesel as alternative fuel: Experimental analysis and energetic evaluations. Energy 2011;29:2195–2211.
[13] Altin R, Cetinkaya S, Yucesu HS. The potential of using vegetable oil fuels as fuel for diesel engine, Energy conversion and management 1991;42:529-538.
[14] Aydin H, Bayindir H. Performance and emission analysis of cottonseed oil methyl ester in a diesel engine. Renewable Energy 2010;35:588-592.
[15] Ghobadian B, Rahimi H, Nikbakht AM, Najafi G, Yusaf TF. Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. Renewable Energy 2009;34:976-982.
[16] İlkılıç C, Aydın H. Fuel production from waste vehicle tires by catalytic pyrolysis and its application in a diesel engine. Fuel Procesg Technol 2011;92:1129–35.
[17] Huang J, Wang Y, Qin J-B, Roskilly AP. Comparative study of performance and emissions of a diesel engine using Chinese pistache and jatropha biodiesel. Fuel Process Technol 2010;91:1761–7.
[18] Ndayishimiye P, Tazerout M. Use of palm oil-based biofuel in the internal combustion engines: Performance and emissions characteristics. Energy 2011;36:1790-6.
[19] Mittelbach M, Remschmidt C. Bio-diesel: the comprehensive hand book, ISBN 3 200-00249-2.
[20] Gumus M, Kasifoglu S. Performance and emission evaluation of a compression ignition engine using a biodiesel (apricot seed kernel oil methyl ester) and its blends with diesel fuel. Biomass and bioenergy 2010;34:134 –9.
[21] Xue J, Grift TE, Hansen AC. Effect of biodiesel on engine performances and emissions. Renewable and Sustainable. Energy Reviews. 2011;15:1098–1116.
[22] Çelikten I, Mutlu E, Solmaz H.. Variation of performance and emission characteristics of a diesel engine fueled with diesel, rapeseed oil and hazelnut oil methyl ester blends. Renewable Energy 2012; 48:122-126.
[23] Agarwal AK. Biofuels (alcohols and biodiesel) applications as fuels for internal combustion engines. Progress in Energy and Combustion Science 2007;33:233–71.
[24] Monyem A, Van Gerpen JH., Canakci M. The effect of timing and oxidation on emissions from biodiesel-fueled engines. Trans ASAE 2001;44:35–42.
[25] Abd-Alla GH, Soliman HA, Badr OA, Abd-Rabbo MF. Effects of diluent admissions and intake air temperature in exhaust gas recirculation on the emissions of an indirect injection dual fuel engine. Energy Convers Manage 200; 42:1033–45.
[26] Lapuerta M, Armas O, Rodriguez-Fernandez J. Effect of biodiesel fuels on diesel engine emissions. Prog Energy Combust Sci 2008;198–223.
[27] Beatrice C, Bertoli C, D'Alessio J, Del Giacomo N, Lazzaro M, Massoli P. Experimental characterization of combustion behaviour of new diesel fuels for low emission engines. Combust Sci Technol 1996;120(1–6):335–55.
[28] Song J, Cheenkachorn K, Wang J, Perez J, Boehman AL, Young PJ, et al. Effect of oxygenated fuel on combustion and emissions in a light-duty turbo diesel engine. Energy Fuel 2002;16(2):294–301.
[29] Doll C, Wietschel M. Externalities of the transport sector and the role of hydrogen in a sustainable transport vision. Energy Policy 2008;36:4069–78.
[30] Selim MYE. Pressure–time characteristics in diesel engine fueled with natural gas. Renew Energ 2001;22:473–89.
[31] Mohamed SY, Selim, Salah B, Al-Omari, Abdullah AJ, Al-Aseery. Effects of Steam Injection to Dual Fuel Engine on Performance, Noise and Exhaust Emission. SAE Paper 2009-01-1831.
[32] Sahoo PK, Das LM. Combustion analysis of Jatropha, Karanja and Polanga based biodiesel as fuel in a diesel engine. Fuel 2009;88:994–99.
[33] Rao GLN, Sampath S, Rajagopal K. Experimental Studies on the Combustion and Emission Characteristics of a Diesel Engine Fuelled with Used Cooking Oil Methyl Ester and its Diesel Blends. Int J App Sci Eng Technol 2008;4:64-70.
[34] Zhang Y, Gerpen JHV. Combustion Analysis of Esters of Soybean Oil in a Diesel Engine. SAE Paper 1996;960765.

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Influence of fatty acid structure on fuel properties of algae derived biodiesel

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Abstract

Physical and chemical properties of biofuel are influenced by structural features of fatty acid such as chain length, degree of unsaturation and branching of the chain. A simple and reliable calculation method to estimate fuel property is therefore needed to avoid experimental testing which is difficult, costly and time consuming. Typically in commercial biodiesel production such testing is done for every batch of fuel produced. In this study 9 different algae species were selected that were likely to be suitable for subtropical climates. The fatty acid methyl esters (FAMEs) of all algae species were analysed and the fuel properties like cetane number (CN), cold filter plugging point (CFPP), kinematic viscosity (KV), density and higher heating value (HHV) were determined. The relation of each fatty acid with particular fuel property is analysed using multivariate and multi-criteria decision method (MCDM) software. They showed that some fatty acids have major influences on the fuel properties whereas others have minimal influence. Based on the fuel properties and amounts of lipid content rank order is drawn by PROMETHEE-GAIA which helped to select the best algae species for biodiesel production in subtropical climates. Three species had fatty acid profiles that gave the best fuel properties although only one of these (*Nannochloropsis oculata)* is considered the best choice because of its higher lipid content.

Keywords: Microalgae; fatty acid; fuel property; biodiesel; PROMETHEE-GAIA.

Nomenclature

FAME	Fatty acid methyl ester
CN	Cetane number
CFPP	Cold filter plugging point (^{0}C)
KV	Kinetic viscosity (mm^2/sec)
HHV	Higher heating value (MJ/kg)
MCDM	Multi-criteria decision method

1. Introduction

A systematic analysis of the fatty acid composition and comparative fuel properties are very important to select the best species for biodiesel production. The particular culture system may significantly influence the algal lipid content and fatty acids structure. The most common fatty acid profiles of algae consist mainly of Palmitic (Hexadecanoic_C16:0), Stearic (octadecanoic_C18:0), Oleic (Octadecenoic_C18:1), Linoleic (Octadecadienoic) and Linolenic (Octadecatrienoic_C18:3) acids [1].Along with these major fatty acids there are varieties of fatty acids in minor amounts which have some influence on fuel property. However there is no single fatty acid that is responsible for any particular fuel property.

The cetane number related to the ignition quality decreases with a decreasing chain length, increased branching, and increased saturation in the fatty acid chain. The higher the cetane number, the better the ignition quality whereas saturated esters, which are advantageous for cetane number possess poor cold-flow properties. Unsaturated, especially poly unsaturated fatty esters improve the cold-flow because of their lower melting points which are desirable but also lower the cetane number and oxidation stability which is undesirable for fuel [2].

These fatty acids have a direct impact on the chemical and physical properties of biofuel. There are methods we can use to derive the fuel properties like cetane number (CN), cold filter plugging point (CFPP), kinematic viscosity (KV), density and higher heating value (HHV) from the fatty acid composition, without experimental tests which can avoid the cost of test and time. The cetane number calculated by ASTM976 is too low when there is a higher number of saturated acids in the ester mixture and a higher number in the mixture with high levels of poly unsaturated acids. Klopfenstein proposed to calculate cetane number based on individual fatty acids [3] which is difficult, expensive and time consuming.

In this study few simple and reliable methods are utilized to estimate some important fuel properties. Cetane number is calculated using Krishnankura [4] proposed method which depends on iodine value and saponification value proposed by Kalayasiri et al.[5]. The degree of unsaturation (DU), long chain saturation factor (LCSF) and cold filter plug point (CFPP) were calculated from fatty acid composition following Remos [6] proposal. L.F.Remirez [7] proposed to calculate physical properties including kinematic viscosity, density, and higher heating value (HHV) from mass fraction of fatty acids.

Selection of species for biodiesel production depends on fuel properties and oil content along with engine performance and emission characteristics. There are multiple-criteria to determine the suitable algae species for biodiesel. A review of the MCDM literature revealed that the PROMETHEE-GAIA approach provides quite useful and clear guidelines for the preferred decision [8] in comparison to other MCDM. The significant advantage of PROMETHEE-GAIA is that it facilitates a rational decision making process which is achieved by virtue of a decision vector that directs the decision makers towards ‘preferred’ solutions [9].

This study applies the PROMETHEE-GAIA algorithm to a calculated data set containing chemical and physical properties of algae derived from fuel and lipid content of nine different algae species. The fatty acids composition is used as criterion along with fuel properties and lipid content to find the influence of individual fatty acids on fuel properties.

2. Materials and methodology

2.1 Algae culture, lipid content and fatty acid methyl ester (FAMEs) analysis

This study was undertaken to characterise suitable species of Algae for biofuel production. There were nine different species including; NQAIF034 *Amphidinium* sp., NQAIF038 *Biddulphia* sp., NQAIF031 *Phaeodactylum tricornutum*, NQAIF284 *Picochlorum* sp., NQAIF010 *Nannochloropsis oculata, NQAIF254 Extubocellulus,* NQAIF294 *Scenedesmus dimorphus,* NQAIF301 *Franceia* sp. and NQAIF303 *Mesotaenium* sp. Each was taken from different growth media but from the same growing environment to investigate their total lipid content and FAME profile using a gas chromatography (GC). There are many successful extraction processes in a laboratory setting but large scale systems in the commercial setting are yet to be developed. In this work, hexane extraction processes are followed in the NQAIF laboratory at James Cook University (JCU) in Townsville, Australia. The composition of fatty acid methyl ester (FAME) analysed from the identified peak on GC standard curve for nonadecanoic (C19:0) acid methyl ester is prepared to quantify the FAME from the GC peak. After concentration is calculated from the peak the fatty acid composition is calculated and shown in percentage in table 1.

Table 1: Fatty acid compositions of nine different algae species (%).

Fatty acid	*Amphidinium* sp.	*Bidulphia* sp.	*Phaeodactylum tricornutum*	*Picochlorum* sp.	*Nannochlopsis oculata.*	*Extubocellulus.*	*Scenedesmus dimorphos*	*Franceia* sp.	*Mesotaenium.*sp.
C8:0	0	0	0	0.1	0.2	0	0	0	0
C10:0	0	0	0	0.1	0	0	0	0	0
C12:0	0	0.5	0	0	0.4	0	0	0	0
C13:0	0	0.4	0	0	0	0	0	0	0
C 14:0	0.8	21	3.3	0.5	5.8	6.6	0	0	0.5
C 15:0	0	0.2	0	0	0	0	0	0	0.5
C 15:1	0	2.2	0.4	0.3	0.5	0.4	0	0	2.3
C 16:0	0	0	0	0	0	0	0	4.3	13.4
C16:1 (7)	36	24	23.6	17	32	25.6	0	25	1.3
C 16:1 (9)	1.1	33	48.2	1.2	30	60.6	4.3	2.7	4.8
C16:2 (7,10)	0	1.7	1.4	5.1	0	2.7	5.5	2.9	2.2
C16:2 (9,12)	0	4.4	4.3	3.5	0	0	4.2	2.4	0.7
C 17:0	0	0	0	0	0	0	41	32.8	0.5
C16:3 (cis 6,9,12)	0	0	0	0.4	0.4	0	1.1	1	0.6
C16:3 (7, 10, 13)	0	0	0	0.3	0.3	0	0	0	1.8
C16:4 (4,7,10,13)	4.1	0.8	0.8	3.4	1	0.9	0	0	16.4
C 18:0	19	1.5	3.6	16	20	3.2	0	0	0.6
C 18:1 (9)	0	0.6	2.3	0	0	0	0	0	5.7
C 18:1 (x)	0	0	0	36	1.3	0	34	16.3	1.9
C 18:2 (cis - 9,12)	0	0	0	15	0	0	2.5	0.8	11.8
C19:0,internal standard	1.4	1.8	1.1	0.7	0.8	1.7	5.3	5.3	2.3
C18:3 all cis 6,9,12	5.7	0	0	2.1	0	0	0	0	1
C 18:3 (all cis - 9,12,15)	0	0	0	0	0	0	2	0.8	30.4
C18:4 (6,9,12,15)	1.1	0	0	0	0	0	0	0	3.1
C 20:2 (cis - 11,14)	12	9.6	12.1	0	8.3	0	0	0	0
C20:5(allcis)5,8,11,14,17)	20	0	0	0	0	0	0	0	0.8
C 22:0	0	0	0	0	0	0	1.1	1.5	0
C 24:0	0	0	0	0	0	0	0.4	0.8	0
C 24:1 (cis - 15)	0	0	0	0	0	0	1	0	0

2.2 Calculation of fuel properties from fatty acid composition

There are many useful methods proposed by researchers to estimate fuel properties from its fatty acid profile. An equation has been proposed by Klopfenstein [3] to estimate cetane number for individual fatty acids. In this case however we use Krisnangkura [4] proposed equation to estimate the cetane number (CN) of algae oil methyl ester based on their saponification value (SV) and iodine value (IV). Kalayasiri et al.[5] presented equations to estimate the SV and IV from fatty acid methyl ester composition. Ramos et al.[6] proposed equations to calculate the degree of unsaturation (DU) based on the amount of mono unsaturated and poly unsaturated fatty acids whereas the long chain saturation factor (LCSF) and cold filter plugging point (CFPP) lending more weight to the composition of fatty acids with long chains.

Recently Ramirez [7] proposed some empirical equations to estimate cetane number and three physical properties of methyl ester including kinetic viscosity, density and higher heating value. These properties were calculated based on molecular weight and degree of unsaturation of FAME.

2.3 The PROMETHEE-GAIA analysis

Most MCDM problems involve several criteria. As a result, the solution of the problem exists in a multi-dimensional space. The GAIA (Graphical Analysis for Interactive Assistance) component of the PROMETHEE-GAIA algorithm performs Principal Component Analysis (PCA) to reduce the dimensionality of the problem to 2 spatial dimensions (called the GAIA plane) for visual interpretation of the problem.

Unlike PCA, PROMETHEE-GAIA has a critical difference in that it provides a decision vector for the analyst. This enables the decision maker to view different alternatives in the GAIA plane, and to be directed towards preferred solutions by the decision vector. The theory of the PROMETHE-GAIA algorithm is well described in literature [8-16].

In this study some estimated biodiesel properties (cetane number, iodine value, cold filter plugging point, kinetic viscosity, density and higher heating value) are analysed with PROMETHEE-GAIA to select the most suitable species for biodiesel production.

3. Results and discussion

Some fuel properties derived from their fatty acid profile by few estimation methods are shown in table 2. Based on these fuel properties and lipid content, suitable algae species need to be chosen for biodiesel production. These MCDM problems have been considered in nine different criteria (five chemical and three physical properties of fuel and lipid content) to select the suitable one from nine different algae species for biodiesel production. All criteria are weighted equally.

Table 2: Derived chemical and physical properties of fatty acid methyl ester.

Criteria		Algae species								
(Fuel property)	Standard	*Amphidinium* sp.	*Bidulphia* sp.	*Phaeodactylum tricornutum*	*Picochlorum* sp.	*Nannochlopsis oculata.*	*Extubocellulus.*	*Scenedesmus dimorphos*	*Franceia* sp.	*Mesotaenium* sp.
LCSF	↓	11.3	2.7	2.8	5.5	3.7	3	3.8	3.1	1.6
CFPP(^{0}C)	-5 to -13	19.1	-7.9	-7.8	0.7	-4.8	-7	-4.6	-6.7	-11
IV	120	159	87.9	114	135	80.6	65.1	183.7	205.5	202
SV	↓	188.2	210	204	195	203	209	195.7	197.5	200
CN_1	51min	39.5	52.5	47.3	44	55	57.8	32.9	27.7	28.3
CN_2	51min	42.9	54.6	50.3	49.0	57.9	60.9	37.1	33.3	33.4
KV (mm2/sec)	1.9-6.0	4.1	3.7	3.7	4.0	4.2	3.9	3.6	3.5	3.4
Density(g/cm3)	0.88-0.89	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9	0.9
HHV(MJ/Kg)	40	40.3	40.0	39.8	39.9	39.8	40.1	40.2	40.4	40.2
%Lipid DW^{-1}	↑	18.9	24.9	21.7	30.5	41.0	27.6			

CN_1: Cetane number derived by Krishnangkura's method. CN_2: Cetane number derived by Ramirez's method.

Iodine value is an indicating parameter of the degree of saturation in fuel which influences the fuel viscosity and cold filter plugging point. The lower the iodine value is the higher CN which means better the fuel and vice versa[17].

Figure 1 presents the relation of fuel properties for each fatty acid. The dependence of long chain saturated factor (LCSF) and cold filter plugging point (CFPP) are the same with fatty acids. SV and CN are associated with the following fatty acids C16:1,7; C8:0; C20:2,c11,14; C12:0; C16:1,9; C13:0; C14:0; C18:0; C18:2allc6,9; and C20:5allc5 whereas IV is fairly allied with fatty acids C10:0; C16:2,9,12; C16:3c6,9,12; C19:0cis; C17:0; C22:0; C24:1c15; C16:2,7,10; C24:0; and C18;1x. LCSF, CFPP are positively related with the following fatty acids C16:0; C18:2c9,12; C18:3,7,10,13; C18:3allc9, C18:4,6,9,12,15; C15:0; C15:1m C18:1,9; and C16:4,4,7,10,13 even though they are showing opposite in the graph. This happened because of the negative value of CFPP. The more the negative value means more closely depends on these fatty acids in the opposite direction. IV and CN are oppositely related with fatty acids.

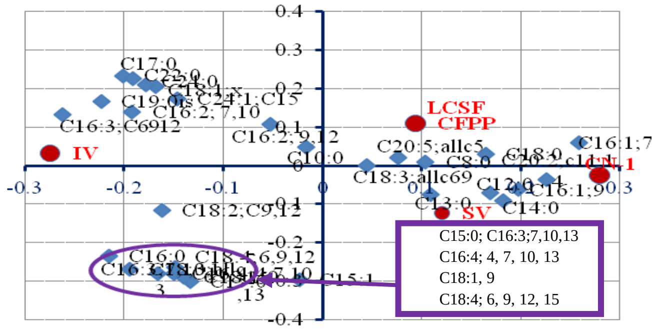


Fig.1. Loadings plot from PROMETHEE data based on fatty acids and fuel chemical properties only.

The relation of fatty acids and physical properties of fuel which are derived by Ramirez's method are shown in figure 2. The following fatty acids, C16:0; C18:3allc9; C16:3,7,10,13; C18:1,9: C15,0; C18:4,6,9,12,15; C16;4,4,7,10,13; C15:1; and C18:2c9,12 have negative influence on KV and CN. HHV and density are associated with the following fatty acid: C170, C220, C190is, C163c6912, C162710, C162912, C181x, C241c15, and C240. CN and KV has positively influenced the fatty acids C10:0; C13:0; C18:0; C16:1,9; C16:1,7; C14:0; C12:0; C18:3allC69, and C20:5allc5. Density is inversely related to the CN and KV of fuel.

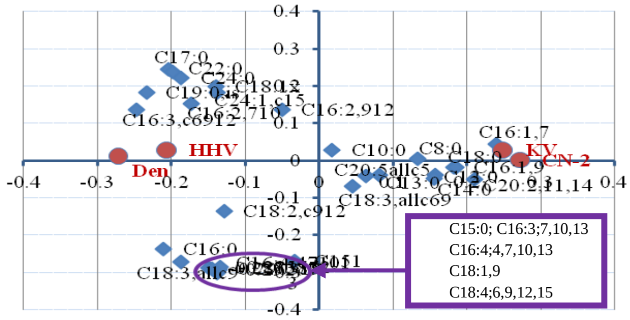
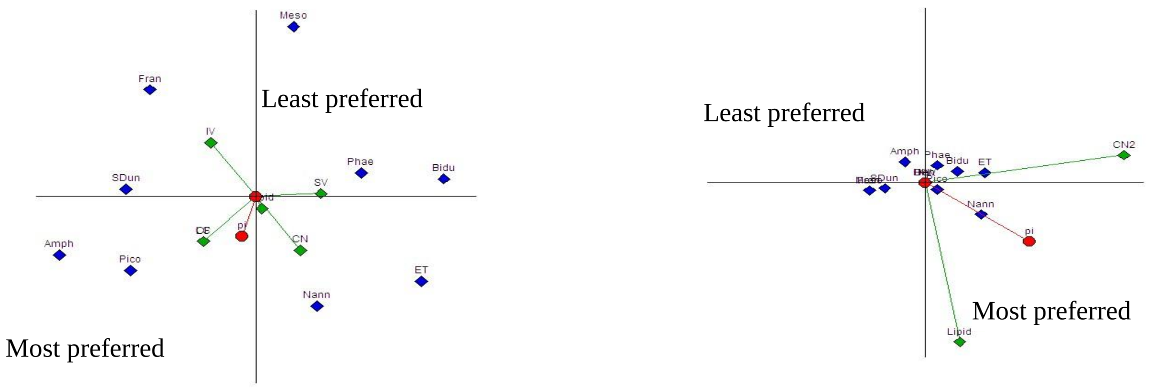


Fig.2. Loadings plot for PROMETHEE based on fatty acids and fuel physical properties only.

In the process of suitable species selection, multiple fuel properties and lipid content is considered for PROMETHEE-GAIA analysis and graphically presented in figure 3(a) and (b). Figure 3(a) shows a clear view of *Nannochlopsis oculata* and is most likely the best choice considering the fuel chemical properties and lipid content. Variance explained by the first two PCs is 93.99%; all variables were maximised and modelled using the usual preference function.



(a) (b)

Fig.3(a). GAIA plot based on fuel chemical properties and lipid only. Fig.3(b). GAIA plot based on fuel physical properties and lipid only

Graphical presentation of algae species selection influenced by the fuel physical properties and lipid content is shown in figure 3(b). In interpreting these results, the length of the decision vector (pi) is critical, as a longer decision vector indicates a greater decision making power. Initially the usual preference function was used and the decision vector was shorter therefore linear preference function is used and a stronger decision vector is found. Variance explained by the first two PCs is 100%; all variables were maximised (which means higher variable values are preferred) and modelled using linear preference function and the standard for each as the preference threshold. . Regardless the preference function used, the *nannochlopsis oculata* is chosen to be the best algae species for biodiesel production

4. Conclusion

In commercial biodiesel production it is essential to reduce cost and time with efficient processes. This work provides much needed support to optimise biodiesel production from algae. Our main aim was to investigate the influence of each fatty acid to fuel properties. The higher the poly unsaturated fatty acid, the higher the IV value and lower the cetane number. Kinematic viscosity is highly associated with saturated fatty acids whereas higher heating value increases with higher saturated fatty acids. The process of selecting the best species depended on the fuel properties which PROMETHEE-GAIA provides a clear graphical representation.

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References

[1] G. Knothe, "Improving biodiesel fuel properties by modifying fatty ester composition," *Energy Environ. Sci.,* vol. 2, pp. 759-766, 2009.

[2] G. Knothe, "“Designer” Biodiesel: Optimizing Fatty Ester Composition to Improve Fuel Properties†," *Energy & Fuels,* vol. 22, pp. 1358-1364, 2008.

[3] W. Klopfenstein, "Estimation of cetane index for esters of fatty acids," *Journal of the American Oil Chemists' Society,* vol. 59, pp. 531-533, 1982.

[4] K. Krisnangkura, "A Simple Method For Estimation of Cetane Index of Vegetable Oil Methyl Esters," *JAOCS,,* vol. VoL 63, no . 4 1986.

[5] P. Kalayasiri*, et al.*, "Survey of seed oils for use as diesel fuels," *Journal of the American Oil Chemists' Society,* vol. 73, pp. 471-474, 1996.

[6] M. J. Ramos*, et al.*, "Influence of fatty acid composition of raw materials on biodiesel properties," *Bioresource Technology,* vol. 100, pp. 261-268, 2009.

[7] J. E. R.-R. Luis Felipe Ramírez-Verduzco ⇑, Alicia del Rayo Jaramillo-Jacob, "Predicting cetane number, kinematic viscosity, density and higher heating value of biodiesel from its fatty acid methyl ester composition," *Fuel,* 2011.

[8] M. Behzadian*, et al.*, "PROMETHEE: A comprehensive literature review on methodologies and applications," *European Journal of Operational Research,* vol. 200, pp. 198-215, 2010.

[9] J. P. Brans and B. Mareschal, "The PROMCALC & GAIA decision support system for multicriteria decision aid," *Decision support systems,* vol. 12, pp. 297-310, 1994.

[10] J. P. Brans and B. Mareschal, "PROMETHEE methods," *Multiple criteria decision analysis: state of the art surveys,* pp. 163-186, 2005.

[11] J. P. Brans*, et al.*, "How to select and how to rank projects: The PROMETHEE method," *European Journal of Operational Research,* vol. 24, pp. 228-238, 1986.

[12] M. Dağdeviren, "Decision making in equipment selection: an integrated approach with AHP and PROMETHEE," *Journal of Intelligent Manufacturing,* vol. 19, pp. 397-406, 2008.

[13] W. De Keyser and P. Peeters, "A note on the use of PROMETHEE multicriteria methods," *European Journal of Operational Research,* vol. 89, pp. 457-461, 1996.

[14] P. Karande and S. Chakraborty, "Application of PROMETHEE-GAIA method for non-traditional machining processes selection," *Management science,* vol. 2, 2012.

[15] B. Mareschal and J. P. Brans, "Geometrical representations for MCDA," *European Journal of Operational Research,* vol. 34, pp. 69-77, 1988.

[16] J. P. B. a. P. Vincke, "A PREFERENCE RANKING ORGANISATION METHOD (The PROMETHEE Method for multiple criteria Decision-Making)," *Management science,* vol. 31, pp. 647-656, 1985.

[17] S. C. P V Rao, Richard Brown, Kai-Shen Wu, " Influence of iodine value on combustion and NO_x characteristics of a diesel engine. ," p. 0451, 2010.

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Waste heat recovery from a diesel engine using ammonia as the working fluid

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Abstract

Diesel engine exhaust heat can be utilized to generate additional power by operating a separate Organic Rankine Cycle (ORC). In this work, experiments were conducted to measure available heat from a 60 kW diesel engine. Two shell and tube heat exchangers were purchased from the market and installed in the exhaust system of the engine to investigate the performance of the heat exchanger using water as the working fluid. Using the experimental data, design of the heat exchangers is optimized by computer simulation. This optimized heat exchanger is then used to estimate additional power generation considering actual turbine efficiency. Two heat exchangers were used for this purpose. One is used to generate vapour and the other to generate super-heated vapour. Ammonia is used as working fluid. Water is also used as reference fluid to compare the results. It is found that the proposed heat exchanger was able to produce 14% and 5% additional power by using water and ammonia as the working fluids respectively.

Keywords: Waste heat recovery; Organic Rankine cycle; Diesel engine; Heat exchanger

1. Introduction

High usages of fossil fuel in daily life are causing many problems in the environment. Therefore, energy saving become an important issue in energy generation, industrial world and transportation sector. Transportation sector of an industrial country consumes about 30-40% [1] of the total energy consumptions. Despite the advancement of technologies such as Direct-injection (DI) and Homogeneous Charge Compression Ignition (HCCI) to improve the energy efficiency of the internal combustion engines (ICEs), waste energy utilization is also been focused by many researchers in recent days.

ICE convert chemical energy of the fuel into heat energy through combustion and by utilizing the thermodynamic cycle, some part of the heat energy is converted into effective work to drive the vehicle. The rest is wasted into the environment through cooling system and exhaust system. In general, diesel engines have an efficiency of about 35% and thus the rest input energy is wasted. Despite recent improvements of diesel engine efficiency, a considerable amount of energy is still expelled to the ambient from the exhaust gas. In water-cooled engine about 25% and 40% [2] of the input energy are wasted in the coolant and exhaust gases, respectively. The amount of such loss, recoverable at least partly, greatly depends on the engine load. Johnson [3] found that for a typical 3.0 litre engine with a maximum output power of 115 kW, the total waste heat dissipated can vary from 20 kW to as much as 40 kW across the range of usual engine

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operation. It is suggested that for a typical and representative drive cycle, the average heating power available from waste heat is about 23 kW.

As mentioned before, exhaust gas from diesel engine contains significant portion of input energy, it can be an important heat source that may be used in a number of ways to generate additional power and improve overall engine efficiency. These technical possibilities are currently under investigation by research institutes and engine manufacturers. Turbo compounding and bottoming Rankine Cycle (RC) is relatively new technologies than the conventional heat recovery technologies like turbocharging, cabin air-heating [4], desalination [5]. A Rankine cycle using water as working fluid is not enough efficient to recover waste heat below 640°C [6]. In that case, the Organic Rankine Cycle (ORC) is a promising process to recover the heat from the exhaust of an engine and to generate electricity from it [4, 5]. The ORC works like a simple RC but uses an organic working fluid instead of water. A question, which also has to be considered for using ORC, is whether an organic substance is really better than water as working fluid for a given task.

A systematic approach towards using an installation based on the RC in truck applications dates back to the early 1970s where a research program funded by the US Department of Energy (DOE) was conducted by Mack Trucks and Thermo Electron Corporation [7-9]. Under this program, an ORC system was installed on a Mack Truck diesel engine and the lab test results revealed an improvement of bsfc of 10–12%, which was verified by highway tests. During the following years similar research programs were performed by other research institutes and vehicle manufacturers. Aly [10] was able to produce 16% additional power from the exhaust of a Mercedes-Benz OM422A diesel engine by using R-12 as working fluid for the ORC. ORC systems with capacities from 750 to 1500 kWe were examined by Koebbman [6]. Recently, the solution of Rankine Cycle Systems has increased its potential competitiveness in the market even more [11, 12]. This is a result of technical advancements in a series of critical components for the operation of such an installation (heat exchanger, condenser and expander) but also stems from the highly increased fuel prices. Nowadays, the installation of a Rankine Cycle is not only considered as a feasible solution for efficiency improvement in heavy duty diesel engines for trucks [13, 14] but also for smaller application such as passenger cars [15].

With the exception of turbo-compounding, RC- and ORC-based heat recovery systems need to utilise heat exchangers to extract energy from the exhaust gas. The heat exchanger design is critical as it needs to provide an adequate surface area in order to cope with the available heat and to be retrofitted in an existing engine exhaust system. Pressure loss across the heat exchangers also needs to be reasonable to avoid back pressure that will have a negative impact on the net engine power and efficiency.

In this project, experiments were conducted to measure the exhaust heat available from a 60 kW automobile engine at different speeds and loads. A shell and tube heat exchanger was purchased and installed to the engine exhaust system. Experiment was conducted to validate the concept of extracting heat from the exhaust with water. Then with the available data, computer simulation was carried out to optimize a heat exchanger for ORC using ammonia. Water was also used as reference for comparison. For the current study, ammonia is selected considering some suitable features of this fluid for ORC [16]. The optimized model of the heat exchanger was then simulated to generate super-heated vapour. Finally, power output from the turbine is calculated considering isentropic efficiency of actual turbines [17, 18].

2. Experimental Setup

The engine used in this study was a 4-stokes, 4 cylinders, water cooled Toyota 13B diesel engine which is used in pick-up vans. The specification of the engine is presented in Table 1. The engine was coupled with a hydraulic dynamometer. The schematic of the experimental setup is shown in Fig. 1.

A nozzle was mounted at the air inlet of the engine to measure the air-flow rate. The pressure difference across the nozzle was measured with an accuracy of ±0.01 kPa using an inclined manometer. For fuel measurement, a digital weighing scale with an accuracy of ±1 g and a stop watch was used. From the measured air and fuel mass flow rates, exhaust mass flow rate was calculated. Thermo couples of K type were used to measure the temperatures at different points. Burdon tube pressure gauges were used to measure the cold and

Table 1. Engine specification.

Engine model	*13B*
Make	Toyota
Type of engine	4 cylinder water cooled diesel engine
Bore	102 mm
Stroke	105 mm
Compression ratio	17.6:1
Torque	217 N.m @ 2200 rpm

hot fluid side pressures in the heat exchangers. A Dwyer model VFA variable area flow meter was used to measure the water flow rate into the heat exchangers. The flow meter had an accuracy of ± 5%. Engine speed was measured by a digital tachometer with an accuracy of ±1 rpm.

The engine was tested at different loads with variable speeds. The exhaust temperatures and air flow rate were recorded to calculate available heat energy from the exhaust. Then the exhaust of the engine was connected to two shell and tube heat exchangers to study the performance of the heat exchangers. Water mass flow rate, water temperature and pressure were recorded to calculate the effectiveness of the heat exchangers. These data were used to optimize the design of the heat exchanger by computer simulation. The exhaust from the engine was flowed through the tubes of the heat exchangers and the water flowed through the shell side. Counter flow heat exchanger orientation was selected for this study.

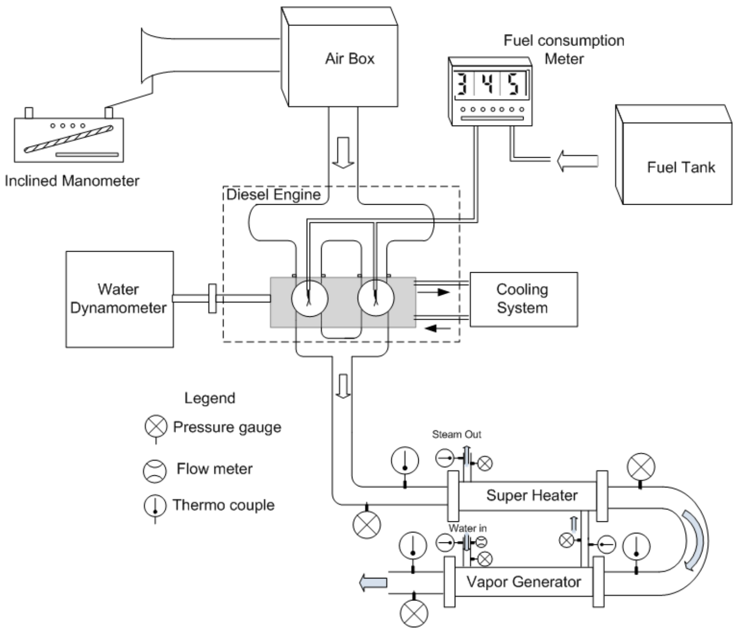

Figure 1: Experiemntal setup

3. Heat exchanger design optimization

Two identical shell and tube heat exchangers possessing a shell diameter of 76 mm, 7 tubes with a diameter of 20 mm and length of 1 m were purchased from the market. They were then fitted into the exhaust of the engine and experiments were conducted to estimate the additional power conceivable with this setup. As these heat exchangers were not optimized for this particular application, attempts were made to design heat exchangers that achieved maximum additional power. Simulation tools were used to simulate the current heat exchangers using dimensions of the purchased heat exchangers and experimental data. After acquiring adequate agreement of simulation results with the experimental results, the effects of important parameters of heat exchanger such as length, number and diameter of tubes on the performance of the heat exchangers were investigated. The potential additional power was then calculated using actual turbine efficiency [17, 18]. As steam expands in turbines, the steam in this application needed to be super-heated. Therefore, two heat exchangers were used: one heat exchanger was used to generate vapor from the liquid namely vapor generator and the second heat exchanger was used to generate super-heated vapor namely super heater.

4. CFD modeling

As mentioned previously, the purchased heat exchangers were modeled and then simulations were carried out first to obtain satisfactory results and then different geometrical aspects of the heat exchanger were optimized. The existing heat exchanger model drawing was created by Computer Aided Design (CAD) software SolidWorks2011. In the model, 30° triangular staggered array layout was used for the tube arrangement of the heat exchanger. The geometry model was then meshed using ANSYS meshing software. The ANSYS CFX13.0 was used to solve the equations for the fluid flow and heat transfer analysis.

In order to make the simulation more accurate, different meshing schemes were used. The solid tubes were meshed using sweep mesh whereas the fluid volumes were meshed using tetragonal-hybrid elements. The final refined mesh was selected by comparing the simulation results of model with different mesh density and meshing schemes. The final model has 10,763,968 elements and 4,263,337 nodes and grid independent solution was acquired.

5. Results and Discussions

To design an effective heat exchanger for heat recovery from the exhaust of an engine, it is required to know how much energy is available in the exhaust. So some base line tests are performed. The exhaust gas temperature at various speed and engine power is presented in the Fig. 2. It is found from the figure that engine power and the temperature of the exhaust gases for all three engine speeds show an approximately linear relationship. Exhaust gas temperature increases with increase of power output and speed of the engine. This indicates that heat recovery will be more viable for higher powers. The maximum exhaust gas temperature was found 665ºC at the engine power of 55.4 kW. This point was selected for the optimization of the heat exchangers.

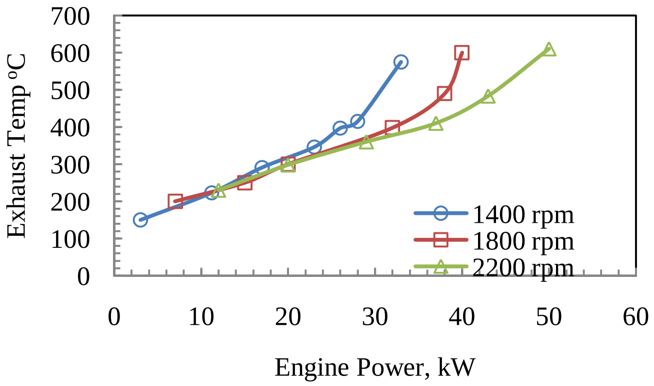

Figure 2: Exhaust gas temperature variation with engine power.

Based on the available data from the experiment, the heat exchanger design was optimized by computer simulation. Fig. 3(a) shows that the effectiveness of the heat exchanger increases with the increase of number of tubes for both working fluids. It is evident that as the number of tubes increases, the effectiveness also increases due to the increase of the surface area of tubes and the effective velocity inside the shell. The highest effectiveness was found to be 0.74 for 19 tubes for water and this number of tube was selected for the next study. The next parameter of the heat exchanger investigated was the length and the results are presented in Fig. 3(b). By observing the figure, it is found that the effectiveness increases with lengths up to 2 meters. If the length of the heat exchanger is longer, the residence time of the cold and hot fluid is more and thus causing more heat transfer. Hence, a longer heat exchanger will have higher effectiveness. The maximum effectiveness

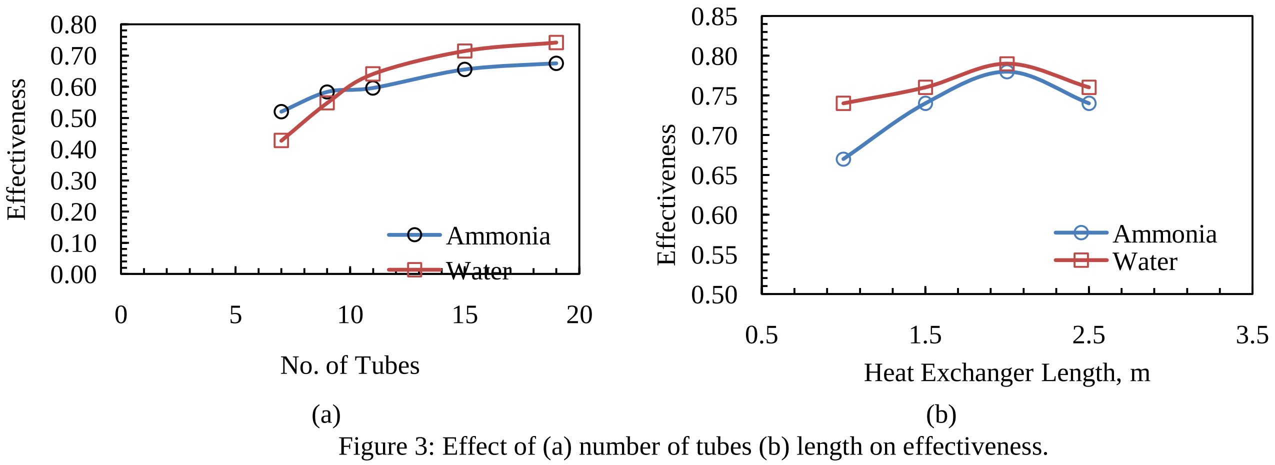

Figure 3: Effect of (a) number of tubes (b) length on effectiveness.

was found 0.79 for 2 m length of the heat exchanger and this length was selected for the proposed heat exchanger. The details of the heat exchanger specification are presented in Table2. In the previous work it was shown that the effectiveness of the heat exchanger decreases with increasing shell diameter [16, 19]. Rubaiyat and Bari [19] found that there is no significant effect of working pressure on heat exchanger effectiveness for different parameters of the heat exchanger. They also found that average pressure drop for different parameter of heat exchanger was about 250 Pa.

Table 2. Heat exchanger specification.

Heat exchanger type	Shell and tube counter flow, hot fluid in tubes and cold fluid in the shell
Shell inside diameter	76 mm
No of tube	19
Tube inside diameter	10 mm
Length of the heat exchanger	2 m

Extra power that can be recovered from the exhaust of the diesel engine with the proposed shell and tube heat exchanger model is presented in the Fig. 4. It is found that additional output power increases as the working pressure increases for all two working fluids. This is because the condensing pressure was kept constant and as the working pressure increases the enthalpy drop across the turbine also increases. From the figure it is clear that water can recover heat most efficiently from the exhaust of the engine than the other organic fluid ammonia. This is because water has very high enthalpy drop across the turbine compared to ammonia. The proposed shell and tube heat exchanger can recover maximum 14% and 5% additional power from the exhaust of the diesel engine using water and ammonia as working fluid respectively considering 70% isentropic efficiency of the turbine [17, 18].

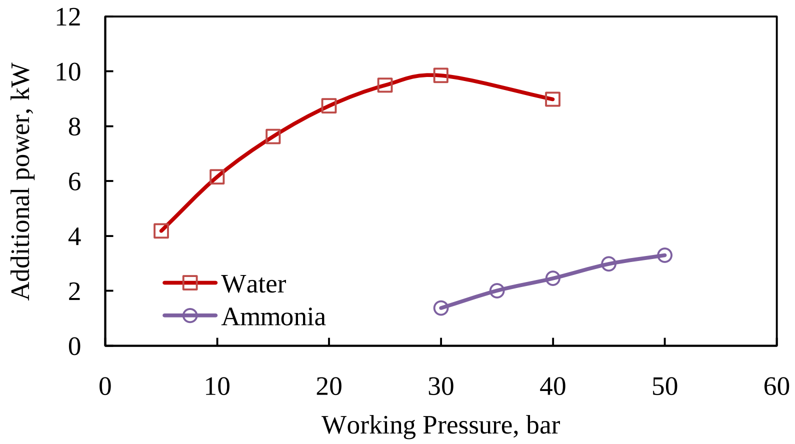

Figure 4: Additional power output variation for different working fluids with working pressure.

6. Conclusion

The exhaust of a diesel engine contains 40% of the input energy and usually this energy is wasted by expelling to the environment. The overall efficiency of the diesel engine can be improved by recovering this waste heat to produce additional power by turbine using ORC. In this project, experiment was conducted to estimate available energy in the exhaust gas of a diesel engine and the experimental data was used to improve the design of the existing shell and tube heat exchanger by computer simulation. The effectiveness of the optimized heat exchanger is found 0.79. Using this optimized heat exchanger 14% and 5% additional power is generated by using water and ammonia as working fluids assuming 70% isentropic efficiency of the turbine.

References

[1] M. He, X. Zhang, K. Zeng, and K. Gao, "A combined thermodynamic cycle used for waste heat recovery of internal combustion engine," *Energy,* vol. 36, pp. 6821-6829, 2011.
[2] M. Hatazawa, H., Sugita, T.,Ogawa, Y.,Seo, "Performance of a thermoacoustic sound wave generator driven with waste heat of automobile gasoline engine," *Transactions of the Japan Society of Mechanical Engineers (Part B,* vol. 70, pp. 292–299, 2004.
[3] V. Johnson, "Heat-generated cooling opportunities in vehicles," *SAE Technical Papers* 2002.
[4] S. Jiangzhou, R. Z. Wang, Y. Z. Lu, Y. X. Xu, and J. Y. Wu, "Experimental study on locomotive driver cabin adsorption air conditioning prototype machine," *Energy Conversion and Management,* vol. 46, pp. 1655-1665, 2005.
[5] T. C. Hung, M. S. Shai, and B. S. Pei, "Cogeneration approach for near shore internal combustion power plants applied to seawater desalination," *Energy Conversion and Management,* vol. 44, pp. 1259-1273, 2003.
[6] T. Hung, T. Shai, and S. Wang, "A review of organic Rankine cycles (ORCs) for the recovery of low-grade waste heat," *Energy,* vol. 22, pp. 661-667, 1997.
[7] F. DiBella, L. DiNanno, and M. Koplow, "Laboratory and on-highway testing of diesel organic Rankine compound long-haul vehicle engine," *SAE Technical Papers* 1983.
[8] E. Doyle, DiNanno, L, Kramer, S, "Installation of a Diesel-Organic Rankine Compound Engine in a Class 8 Truck for a Single-Vehicle Test," *SAE Technical Papers* 1979.
[9] P. Patel, Doyle, EF, "Compounding the Truck Diesel Engine With An Organic Rankine-Cycle System," *SAE Technical Papers* 1976.
[10] J. Larjola, "Electricity from industrial waste heat using high-speed organic Rankine cycle (ORC)," *International journal of production economics,* vol. 41, pp. 227-235, 1995.
[11] S. Hounsham, Stobart, R, Cooke, A, Childs, P, "2008-01-0309 Energy Recovery Systems for Engines," *SAE SP,* vol. 2153, p. 79, 2008.
[12] M. Kadota and K. Yamamoto, "Advanced transient simulation on hybrid vehicle using Rankine cycle system," *SAE International Journal of Engines,* vol. 1, p. 240, 2009.
[13] C. Nelson, "Exhaust Energy Recovery," presented at the Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Dearborn, Michigan, 2008.
[14] R. W. Kruiswyk, "An Engine System Approach to Exhaust Waste Heat Recovery," presented at the Diesel Engine-Efficiency and Emissions Research (DEER) Conference, Dearborn, Michigan, 2008.
[15] J. Ringler, M. Seifert, V. Guyotot, and W. Hübner, "Rankine cycle for waste heat recovery of IC engines," *SAE International Journal of Engines,* vol. 2, p. 67, 2009.
[16] S. Hossain and S. Bari, "Effect of different working fluids on shell and tube heat exchanger to recover heat from exhaust of an automotive diesel engine," in *World Renewable Energy Congress* Linköping, Sweden, 2011, pp. 764-771.
[17] M. J. Moran and H. N. Shapiro, *Fundamentals of Engineeering Thermodynamics*, 4th ed. USA: John Wiley & Sons, 2000.
[18] Y. A. Cengel, R. H. Turner, and J. M. Cimbala, *Fundamentals of Thermal-Fluid Sciences*, 3rd ed.: McGrawHill, 2008.
[19] S. N. H. Rubaiyat and S. Bari, "Waste heat recovery using shell and tube heat exchanger from the exhaust of an automotive engine," in *13th Asian Congress of Fluid Mechanics*, Gazipu, Bangladesh 2010.

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Optimization of Energy Extraction from In-stream Water Current: An Application of Ducted Cross-Flow Turbine

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Abstract

Background of undertaking this research is making an attempt to optimize kinetic energy extraction from in-stream water for establish reliable and sustainable green energy source. Based on simulated results a laboratory scale and another prototype cross flow micro hydro turbine have been developed with duct. Developed turbines have been tested in in-stream water bodies which show that turbine had started energy extraction at 0.3 m/s water velocity. Reported results have also shown that 45.86% kinetic energy has been extracted by ducted prototype turbine at water velocity 1.0 m/s by dropping water velocity 18.5% across turbine blades which contributed to generate turbine speed 202 RPM. This study reveals that duct installation at inlet-outlet of CFMHT has contributed to increase energy extraction efficiency. Study concludes that these findings would be greatly useful in future research for developing commercially feasible micro hydro turbine.

Keywords: Turbine; Velocity; Energy; Prototype

Nomenclature

V_i	Inlet water velocity
V_O	Outlet water velocity
RPM	Rotation of turbine per minute
ΔE	Extracted Energy
Ps	Shaft power
Ɵ	Duct Angle
R	Connecting rod of turbine blade
ΔV	Water velocity drop across turbine blade
H	Height of Turbine
D	Diameter of Turbine
A	Blade area of Turbine

1. Introduction

1.1 Background Research

Green House Gases (GHG) is a popular discussing topic around the globe; and the due reason is its adverse effect on environment and economy. Additionally, if fossil fuel burning continues with the same rate for supporting economic growth of the world, GHG may further vigorously act on climate change. In order to address this issue; green energy projects are getting priority to researchers and decision makers. Meaning of green energy is a sources that are not involving in producing emission during its trasformation into electricity. More particularly, 'green energy production' is a term being used to indicate an electricity production source which is free from pollution [1]. Currently, making geen energy popular, commercials are advertizing green power products; and even this concept has been fostering by the relevant authorities to create demands for environmentally fit power generation [2].

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Current research trend on renewable energy sector indicate that in near future dependence on fossil fuel will shift to green energy for sustaining in economic growth and environment protection. Indeed, present contribution from green energy to total global energy demand is about 10%; and rest 90% energy is supplying from fossil fuel which appears threat to environment [3]. Relevant literatures have demonstrated that burning of huge amount of fossil fuel climate is getting change towards worse with significant adverse effect [4].

Eventual challenge of this century for policymakers is to develop and manage an adequate, affordable and reliable energy production system to have sustainable environment for economic development [5]. Indeed, this research is a response to this heart burning issue.

1.2 literature Review

Nowadays micro-hydro project is becoming popular for extracting green energy due to its various advantages such as; production of low cost electricity, environment friendly, involving low level technology and finally suitable for off grid areas [6]. Recent studies on energy sources suggest that green energy is reliable and environmentally friendly compare to conventional energy sources [7]. Moreover, this source provides solution with energy supply for remote and hilly areas where the extension of grid system is not economically and technically feasible [8]. In technological point of view, Cross-Flow Micro Hydro turbine (CFMHT) is easy to fabricate and install; and for capitalizing these benefits a few companies in developed counties have putting efforts to produce this turbine at commercial scale.

CFMHT family has been divided into a few groups. Based on alignment of rotor axis with respect to water flow, this turbine family has been divided into two groups, namely, axial flow and cross flow turbine. In a technical report Hydrovolt Inc. has stated that the axial flow turbine has an axis parallel to water flow, while, the cross flow turbine has vertical axis to water flow [9]. Further, cross flow turbine has been divided into two groups such as vertical axis and in-plane axis. Vertical axis turbine has the axis vertical to water plane and in-plane axis turbine has axis on horizontal plane of water. Examples for vertical axis turbine are SC-Darrieus, H-Darrieus, Darrieus, Gorlov and Savonius [9]. General feature of cross flow turbine is shown In Figure 1[6].

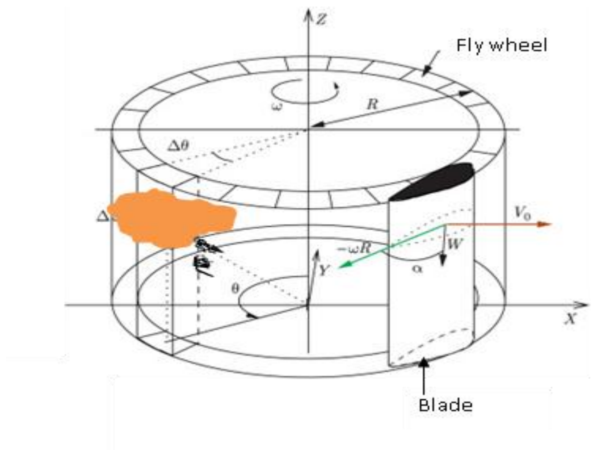

Fig.1. Fundamental of Vertical type CFMHT

Currently Darrieus Turbine is being manufacturing by Alternative Hydro Solutions Ltd which typically consists of five air foil blades, arms and shaft. This turbine can be mounted on pontoon, barge, or small boat. This turbine is available in several diameters such as 1.25m, 1.5m, 2.5m, 3.0m, and 6.0m. Study shows that power generation from this turbine depends on dimension of blade; and water source and its energy extraction efficiency is moderate [10].
Cross-axis turbine, known as Kobold Turbine, is currently producing by Ponte di Archimede S.p.A which has three straight blades, and mounted under a buoy. This turbine was installed in Strait of Messina in 2001 and generated about 2 kW at

water velocity 2.0 m/s. A stronger rotor bearing was installed at shaft to produce less friction; and energy extraction efficiency of this turbine was found about 25% [10].

EnCurrent Hydro Turbine is a vertical axis Darrieus type cross flow axis turbine with five straight blades; and it was tested with ducted and non-ducted configurations. Three types of EnCurrent turbine was tested early 2006 that produced 5 kW, 10 kW and 25 kW with maximum water velocity 3 m/s. This turbine was able to extract about 40% energy from in-stream water [10].

Gorlov Helical Turbine (HGT) consists of three helical blades like screw thread. Helical airfoil blade provides thrust on perpendicular to leading edges of blades that can pull them very faster compare to other turbines. GHT is suitable to operate at low speed in-stream such as 0.6 m/s for capturing kinetic energy. Standard unit of GHT is 1 meter in diameter by 2.5 meter in length; and it can work in tides, non-tidal rivers, or ocean currents at a moderate efficiency [11].

A join research program, University Malaysia and JKR a department of Malaysian government has been started 2010 for developing higher efficient vertical type CFMHT known as JARIMAS. Preliminary findings of this research show that energy extraction from in-stream water is still moderate [12, 13]. Results of the above studies suggest that further research is essential for improving energy extraction efficiency; indeed, to address this issue current research project has been undertaken.

2. Research Objectives

The broad objective of this study is to determine effect of duct installation on CHMHT performance and the specific objectives are to estimate the effect of duct on:

- Energy Extraction
- Velocity Drop Across Turbine Blades
- Rotation of Turbine

3.0 Research Methodology

Mode of study on CFMHT is multi-fold such as literature review for collecting latest information on the relevant issue, simulation of mathematical models, and finally developing and testing of laboratory scale and prototype CFMHT in low speed in-stream water body. Strategic plan of main research has been shown in Figure 2.

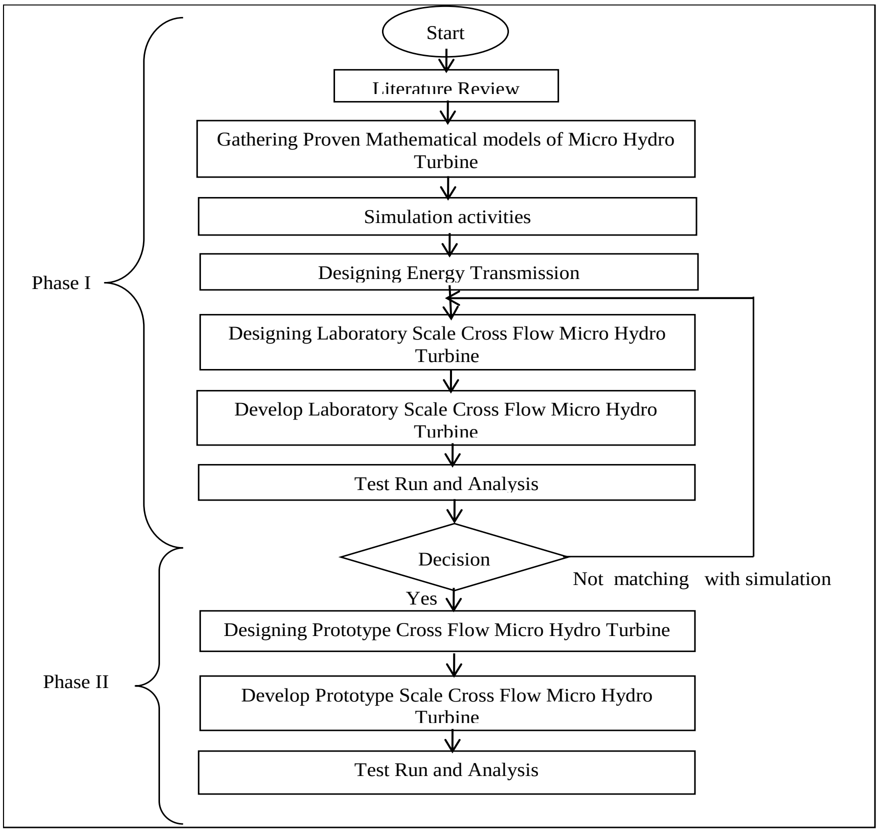

Fig. 2. Strategic Plan of Research on CFMHT

3.1 Research Design

This study is a part of research on CFMHT shown in Figure 2 and it belongs to research phase II. Main functions of this research are to measure inlet (V_i) and outlet (V_o) water velocity, rotation (RPM) of turbine shaft and energy extraction. For conducting this study an experiment setup has been designed with two ducts for test run of CFMHT in a in-steam water at velecity range 0.3m/s to 1.0 m/s.
Available mathamtical models relating to energy extation from in-stream by CFMHT has been selected and used for estimaing peramenters of research objectives. In order to reduce estimating error, statistical quality cntrol technique has been selected for data analysis which includes 3 standard deviations of normal distribution (3σ).

3.2 Designing Experiment Setup

For measure effect of duct on turbine performance entire expeiment has been divided into three parts which includes turbine operations without duct, with one duct at water inlet and with two ducts both at inlet and outlet; and basic arrangment has shown in Figure 3.

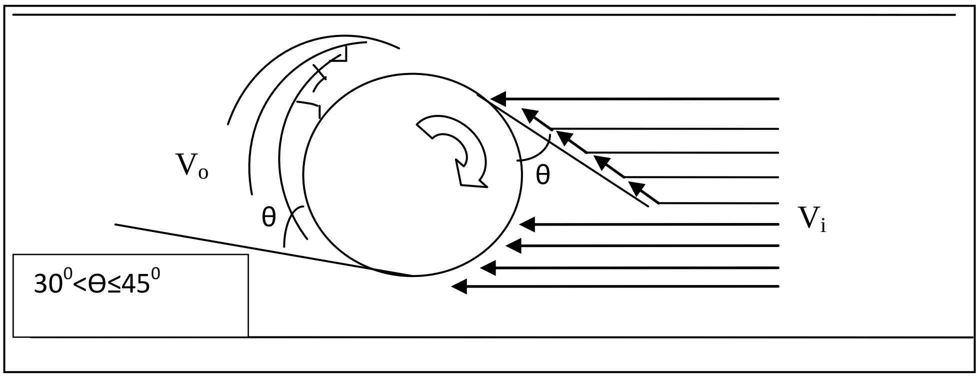

Fig.3: Duct arrangement in CFMHT

3.3 Theoretical Framework

It has been reported that energy contents in water stream is depending on water density and its velocity [14]. A schematic process diagram of energy extraction and transformation to shaft power is shown in Figure 4.

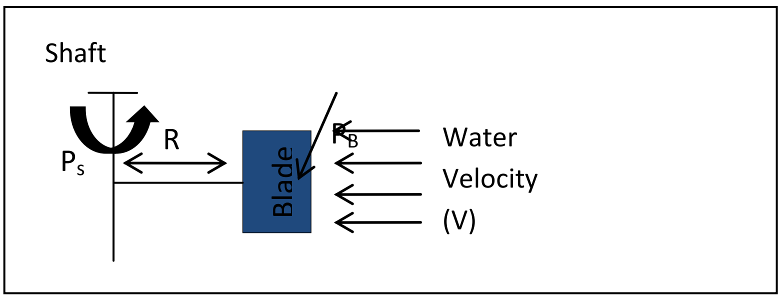

Fig 4: Schematic process diagram of energy extraction and transformation

3.3.1 Measuring In-stream Kinetic Energy

General equation of kinetic energy contents in in-stream water is usually presented by following expression [11]:

$$Energy\ (E) = 1/2\rho CPAV3 \quad (1)$$

Where, ρ = Water Density (kg/m^3), C_k = Power coefficient, A = Turbine blade area (m^2),
V = Velocity of Water m/s

$$Energy\ extraction\ by\ CFMHT\ (\Delta E\%) = (Vi3 - Vo3)/Vi3 \quad (2)$$

3.3.2 Measuring Velocity Drop across Turbine

When water current passes through turbine a certain amount of kinetic energy release to blade and corresponding amount of velocity has dropped. This amount can be estimated from equation shown as below:

$$Velocity\ drop\ across\ turbine\ blades\ (\Delta V\ \%) = (Vi - Vo)/Vi \qquad (3)$$

3.3.3 Turbine Rotation

Rotation of turbine (RPM) depends on amount of energy has been extracted by CFMHT [10], CFMHT RPM can be directly measured by using tachometer, or even from simulation.

4. Test Run and Data Analysis

Laboratory scale CFMHT (Dimension H=0.2 m, D=0.24 m, A=0.09 m^2) has been installed in an open water channel and test run conducted at various water velocity. Equation (2) and (3) has been estimated by using turbine operating data. Table 1 and Table 2 present analytical findings of test run.

Table 1: Laboratory Scale Turbine Testing without Duct

V_i (m/s)	V_o (m/s)	ΔV (%)	ΔE (%)	RPM
0.25	0.227	9	25.5	35
0.3	0.270	12	33.3	35
0.35	0.305	14	34.4	37
0.4	0.292	16	40.78	45
0.5	0.437	17.5	43.5	67

Table 2: Laboratory Scale Turbine Testing with Duct Angle 450/45^0

V_i (m/s)	V_o (m/s)	ΔV (%)	ΔE (%)	RPM
0.25	0.225	10	27.0	40
0.3	0.258	14	36.5	43
0.35	0.297	15.5	41.9	50
0.4	0.332	17	42.8	55
0.5	0.405	19	46.6	80

Table 1 and 2 demonstrate impact of duct on energy extraction. It is evident that at duct angle 45^o (both inlet and outlet) turbine has extracted 46.6 percent energy from water and this value is highest amount in that experiment. It means that duct contributed to create an extra thrust on blades which leads to generate 80 RPM; and this finding indicates duct created effect on power extraction. Based on these research outcomes, this research program has been extended to conduct further test with a prototype CFMHT to investigate about its operating charactering in-stream water. The findings of test runs are reported in Table 3 and Table 4.

Table 3: Testing of Prototype CFMHT at Low Water Speed

At Water Velocity 0.3m/s	Without Duct	Duct at Inlet 45^0	Duct at inlet-outlet $45^0/45^0$
Velocity Drop, ΔV (%)	12	14	16
Power Extraction, ΔE (%)	31.85	36.3	40.7
RPM	96	120	152

Table 4: Testing of Prototype CFMHT at Moderate Water Speed

Water Velocity 1 m/s	Without Duct	Duct at Inlet 45^0	Duct at inlet-outlet $45^0/45^0$
Velocity Drop, ΔV (%)	13.5	15.2	18.5
Power Extraction, ΔE (%)	35.2	39.6	45.86
RPM	131	141	202

Table 3 and 4 demonstrate that at duct angle 45^o (both inlet and outlet) turbine at a water velocity 1 m/s has extracted 45.86 percent energy from water and it is highest amount in that experiment. This finding is similar with results obtained from laboratory scale CFMHT. These findings suggest that duct at let-out of CFMHT able to increase energy extraction efficiency.

5.0 Findings and Discussion

Referring to test result of laboratory scale CFMHT, duct and without duct, at water velocity 0.5 m/s, 12% increasing in velocity drop had found across turbine which contributed to increase about 8.5% energy extraction with increasing of 32% RPM. Test run of prototype at water velocity 0.3 m/s with ducting system, both at inlet and outlet, results show increasing of 23% energy extraction with increasing turbine RPM from 120 to 152 and velocity drop increased from 14% to

16%. While same CFMHT was tested at water velocity 1 m/s, energy extraction was found 33% higher with velocity drop about 18.5%. Based on these experimental findings, it can be stated that duct holds power to increase energy extraction from in-stream water; and eventually contributed to increase operating performance of CFMHT.

5.1 Practical Implication of Research Findings

In-stream CFMHT is a useful machine for extracting low cost green energy; and the model reported in this paper would be greatly useful in increasing its extraction efficiency. These findings would insist policy makers for commercializing CFMHT; and it may commercially feasible for manufacturing SME, agriculture projects and residence nearby river for boost up economy.

5.2 Social Implication of Research Findings

Approach used in this study would be an effective way of extracting higher percentage of green energy from in-stream water and to increase turbine operating performance; Of course, higher green energy performance would contribute to increase environmental sustainability; thus society would be benefited by using this model.

5.3 Conclusion

Findings of this study suggest that duct installation at let-out of CFMHT may contribute to increase energy extraction efficiency; and concludes that these findings would be greatly useful in future research for developing commercially feasible micro hydro turbine.

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Reference

[1] Green Energy. (2007). Retrieved May 5, 2011, from *Nuclear Energy and Science for the 21st-Century*: http://www.ifpaenergyconference.com/Green-Energy.html

[2] H.Ballat. (2007, March 19). Contibution of Green Energy Sources to Electrical Power Production of Turke: A Review. (Elsevier, Ed.) Renewable and Sustainable Energy Reviews, 12(2008), 1652-1666.

[3] H.C. Ong *, T. M. (2010, September 15). A review on energy scenario and sustainable energy in Malaysia. *Renewable and Sustainable Energy Reviews, 15*(Energy Reviews 15 (2011)), 639-647 (640).

[4] Sen, (2008). Solar Energy Fundamentals and Modelling Technique. Istanbul, Turkey: Springerlink.

[5] L.Zhimin, T. X. (2004, May 29). Towards green rural energy in Yunnan, China. *Renewable Energy, Renewable Energy 30 (2005) 99–108*, 105.

[6] Hafiza, S., Shahidul,M.I., Rigit, A. R.H., Hafiza, S., Arena, M.L., , Ruduan, A. H.,2011, Is Research and Development on Green Energy Essential for Malaysia? Answer from an Empirical Study, Proceedings of EnCon2011 4th ,Engineering Conference Kuching, Sarawak, Malaysia

[7] Cowan, H., and Harmon, R. (2007). "The Market Case for Green Energy: A Multiple Perspectives Approach." Portland: PICMET *Proceedings:* 2498.

[8] Nathan , R., Ibrahim , H., and Kumaran , P., 2009. Micro Hydro Potential in West Malaysia. International Conference on Energy and Environment , Malacca, Malaysia, IEEE.: 348-359.

[9] Hydrovolt, Inc. 2009. In-Stream Hydrokinetic Turbines: Hydrovolt, Inc. Retrieved September 21, 2010, from Hydrovolt, Inc. Web site availavle at: http://www.hydrovolts.com/MainPages/ Hydrokinetic/Turbines.htm

[10] Verdant Power Canada ULC, 2006. Technology Evaluation of Existing and Emerging Technologies: Water Current Turbines for River Applications, Canada: Verdant Power.":REV-1:10-30

[11] Khan, M. J., Iqbal, M., and Quaicoe, J. 2008.River current energy conversion systems: Progress, prospects and challenges. Renewable and Sustainable Energy Reviews: 2177–2193.

[12] Shahidul, M.I., Rigit, A. R.H., Hafiza, S.,Arena, M.L., , Ruduan, A. H.,2011, ASEANAustralian Engineering Congress 2011, Kuching, Sarawak, Malaysia

[13] Ruduan, A. H.,.Shahidul, M. I., Syed Shazali, S. T.,.Ramji, H., Liakbar.S.M.A, ,2011, Modeling of Green Energy Extraction: An Approach with Cross Flow Micro Hydro Turbine, Proceedings of EnCon2011 4th Engineering Conference Kuching, Sarawak, Malaysia

[14] George,H. and Brian, P. (2006) "Mmothodology for estimating tidal current energy resources and Power

roduction by Tidal In-stream Energy Conversion(TISEC) device."EPRI North America tidal In Stream power feasibilty Demonstration project,Rev 2: 1-15.