

# Investigation of Single Pass Filtration of Tyre Derived Fuel-Diesel Blend

T.J Pilusa, M. Shukla, E. Muzenda

**Abstract**—This research reports the experimental investigation of single pass filtration of tyre derived fuel and low sulphur diesel blend using a bench scale two stage micro-molecular filtration set-up. Crude tyre pyrolytic oil obtained from slow pyrolysis of waste tyres was distilled at 250°C to recover the light to medium fraction from the oil. The distillate was characterized and blended with low sulphur diesel at a volume ratio of 1.5:1 for bench scale filtration tests. Optimum packing densities for both micro and molecular filter media were determined followed by single pass filtration to evaluate the contaminants removal efficiencies. It was observed that the selected packing density of 168kg/m<sup>3</sup> and pattern for micro filter medium can remove up to 2.5µm particle size in the fuel. The 18% reduction in total sulphur in the fuel after filtration was an indication of liquid phase mass transfer (molecular filtration) on the active surface of the molecular sieves.

**Keywords**—Clean Fuel, Compression, Crude Oil, Ignition, Diesel, Engine Performance, Internal Combustion.

## I. INTRODUCTION

THE use of tyre derived fuel as an alternative fuel for compression ignition engines has been reported in literature [1,2,3]. Murugan et al, 2008 [4] discovered that crude tyre derived fuel cannot be used in any internal combustion engines without further processing to remove contaminants. Cunliffe and Williams, 1998 [2] investigated the composition of oils derived from the batch pyrolysis of tyres and discovered common properties to diesel fuel. Murugan *et al*, 2006 [5] further investigated the use of distilled tyre derived fuel blended with diesel fuel in compression ignition engines. Higher exhaust emissions were observed when more than 80% by volume of tyre derived fuel in the blend was used. However no engine failure or reduced performance was observed. Pilusa and Muzenda, 2013 [3] investigated the physical properties of

distilled tyre derived fuel as a diesel additive. Reference [3] reported that distilled tyre derived oil has lower total sulphur and contamination levels with a high degree of oxidation during storage resulting in formation of asphaltenes.

The presence of asphaltenes in any fuel promotes binding of ultra-fines particle contaminants into larger particles which tends to clog the injector nozzles causing non uniform fuel atomization in the injector system. Asphaltenes have previously been reported to be soft and harmless to the fuel injection system, they are now considered a threat due to the presence of large quantities of ultra-fines particles contaminants in fuels [6]. However the quality of fuel remains the major contributing factor of inefficient combustion and subsequently engine wear and excessive emissions.

There are various fuel properties which affect particulate emissions and fuel economy such as the volatility, density, and the sulphur content in the fuel can be altered by the use of fuel additives [7]. The fuel injection and mixture preparation processes are strongly influenced by properties such as the density, volatility, and viscosity, and particle contamination which are often interdependent.

The demand and cost of conventional fuels such as commercial diesel and gasoline is constantly increasing, calling for urgent action to come up with low cost and environmentally sustainable alternative fuels.

South Africa generates approximately 0.12% of the global new tyre production. In 2011 alone, 7.25 million new tyres, excluding mining tyres and belting, were sold in South Africa, 33% of these tyres were scrapped in 2012. These added to the existing 2.55 million tons already stockpiled across the country [8]. Pilusa *et al.* (2013) [9] conducted a study to investigate the economic feasibility of operating a modular waste tyre pyrolysis plant with a total treatment capacity of 30 tons per annum. The study showed a potential return on investment and gross margin of 29.79% and 34.59%, respectively based on capital injection of \$4.27 million at a total operating cost of \$213/ton. Considering the availability of the waste tyres in South Africa, an estimated 43 million liters of tyre derived fuel can be produced from waste tyres in South Africa alone.

These tyres can be potentially turned into low cost alternative fuel that can be blended with low sulphur diesel for application in conventional diesel engines. Reduction of total fuel contaminants is critical in protecting the fuel injection

Jefrey Pilusa is with the Department of Mechanical Engineering Science at the University of Johannesburg, Auckland Park, South Africa (corresponding author: phone: +27 10 210 4813; fax: +27 10 210 4800; e-mail: [pilusat@webmail.co.za](mailto:pilusat@webmail.co.za))

Mukul Shukla is an Associate Professor, <sup>a</sup>University of Johannesburg, Department of Mechanical Engineering Technology, PO Box 17011, Doornfontein 2028, Johannesburg, South Africa; <sup>b</sup>Mechanical Engineering Department, MNNIT, Allahabad 211 004, UP, India MNNIT, ALLAHABAD, 211 004, UP, India, e-mail: [mshukla@uj.ac.za](mailto:mshukla@uj.ac.za); [mukulshukla@mnnit.ac.in](mailto:mukulshukla@mnnit.ac.in)

Edison Muzenda is a Full Professor in the Department of Chemical Engineering Technology at the University of Johannesburg, Doornfontein, South Africa e-mail: [emuzenda@uj.ac.za](mailto:emuzenda@uj.ac.za)

system thereby preventing engine wear and improves efficient combustion as well as reduced fuel consumption. This work investigated single pass filtration of diesel-tyre derived fuel blend.

## II. EXPERIMENTAL

### A. Bench Scale 2-stage micro-molecular filtration

The test rig consisted of 5mm diameter silicone tubing, glass tube for holding filter media, and a Buchner funnel connected to a vacuum pump. Pressure gauges were fitted between the filter media and the vacuum pump inlet to measure and monitor resistance across the filter media.

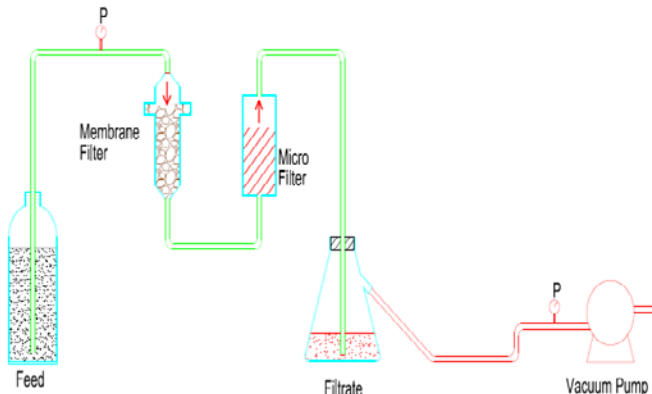


Fig. 1 Two Stage Micro-Molecular Filtration

A blend of 60% distilled tyre derived oil and low sulphur diesel by volume was prepared for this tests. 1000 ml of this blend was filtered through a series of molecular sieves and cotton fibres varying the driving force and micro filter media density. The initial fuel contamination level was measured against the final contamination after the fuel blend has undergone a single pass filtration. The fuel flow rate was measured as a function of filtered fuel collected over time. This was varied by adjusting vacuum level on the pump as shown in Fig 1. The filtration efficiency of the micro filter media (cotton fibres) was evaluated by measuring the particle size fraction of the particle contaminants in the fuel prior to filtration compared to particle size fractions after filtration.

### B. Molecular filter medium

Molecular sieves were used as filter media for the removal of dissolved contaminates in the fuel, mostly sulphur compounds. The effective of this filter media was evaluated by measuring the fuel's initial total sulphur content against the filtered fuel sulphur content. Molecular sieve 13X membranes were obtained from Sigma Aldrich, South Africa. These spherical membranes were 3.2 mm diameter and 34.7 mg per pellet. Each membrane consist of filtering layer which is about 10-15  $\mu\text{m}$  thick. The filtering layer is supported by two layers; an under layer with an approximate pore size of 10  $\mu\text{m}$  and the micro-porous support layer. The total surface area available for filtration was  $0.396\text{m}^2$ . The molecular filtration experiments were

conducted by placing the membranes shown in Fig 2 in a glass tube, Fig.5. Cotton fibres were used at both ends to secure the membrane inside the holder.



Fig 2 Molecular Filter media

### C. Micro filter medium

A bed of filter micro media was formed by compacting natural cotton fibres in a glass tube of 40mm diameter and 100mm long and 30mm cone height, following the padding patterns shown in Fig 3.



Fig. 3 Micro filter media

The fuel was contaminated with a known amount of black toner dust. This fuel was filtered through a layer of packed cotton fibres, increasing the mass of the fibres in the glass tube until the filtrate clarity is clear as shown in Fig.4.

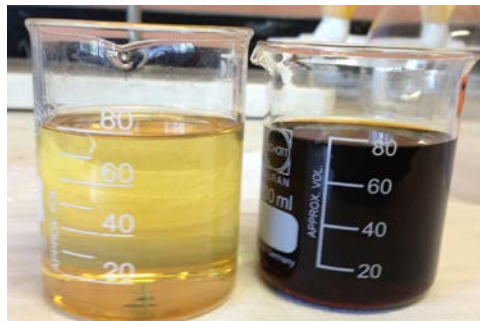


Fig. 4 Filtered and contaminated diesel fuel



Fig. 5 Filter media in glass tubes

## III. RESULTS AND DISCUSSIONS

## A. Theoretical considerations

 i. Filter media packing density

The initial working packing density for the cotton fibres was calculated as a ratio of dry mass of the packed cotton fibres and the active volume of the glass tube as defined in (1).

Pilusa *et.al.*, 2013[10] described the packing density and active filtration area of granular molecular sieves as a function of the media housing geometry and voids between the pellets as defined in (2) and (3). The residence time for efficient mass transfer from the flowing fuel onto the active surface of the granular sieves is defined by (4) as a function of the filter housing geometry and fuel flow rate.

$$\partial_{p-micro} = \frac{12m_c}{\pi D_i^2 (h + 3l_i)} \quad (1)$$

$$\partial_{p-molecular} = \left( \frac{2.526.m_i}{d_i^3 . \pi} \right) \quad (2)$$

$$\kappa = \frac{2.526 . \pi . l_i . D_i^2}{d_i} \quad (3)$$

$$t = \frac{0.10525 . \pi . l_i . D_i^2}{\Phi} \quad (4)$$

$\partial_{p-micro}$  Packing density in (kg/m<sup>3</sup>)

$\partial_{p-molecular}$  Packing density in (kg/m<sup>3</sup>)

$m_i$  Average mass of porous membrane bead (kg)

$m_c$  Total mass of cotton fibres (kg)

$d_i$  Average diameter of porous membrane bead (m)

$l_i$  Active length of filter media housing tube (m)

$h$  Cone height of filter media housing tube (m)

$\kappa$  Active filtration area of molecular filter media (m<sup>2</sup>)

$t$  Fuel residence time (s)

$\Phi$  Fuel flow rate (m<sup>3</sup>/s)

$D_i$  Inside diameter of filter media housing tube (m)

 ii. Molecular filtration (mass transfer in liquids)

An empirical relation for the diffusion molar flux, Fick's first law, defines the diffusion of component A in an isothermal, isobaric system. For diffusion in only the Z direction, the Fick's rate equation is [11]:

$$J_A = -D_{AB} \frac{dC_A}{dZ} \quad (5)$$

$D_{AB}$  - Diffusion coefficient for component A (dissolved contaminants in fuel) diffusing through component B (active layer of molecular sieves).

$\frac{dC_A}{dZ}$  - Concentration gradient in the liquid phase.

Diffusivity coefficient of diesel fuel is nearer to  $3.5 \times 10^{-6} m^2 . s^{-1}$  [12] and about ten thousand times slower than those in dilute gases. This characteristic of liquid diffusion

often limits the overall rate of processes accruing in liquids [11].

$$N_A = k_c \kappa (C_{As} - C_A) \quad (6)$$

$N_A$ , Mass transfer rate (m<sup>3</sup>/s)

$k_c$ , Mass transfer coefficient (m/s)

$\kappa$ , Effective mass transfer area (m<sup>2</sup>)

$(C_{As} - C_A)$ , Driving force concentration difference (%)

Correlations for mass transfer for spherical particles are represented as addition of terms representing transfer by purely molecular diffusion and transfer by forced convection, as defined in (7) [13]

$$Sh = 2 + 0.6 Re^{1/2} Sc^{1/3} \quad (7)$$

$0 \leq Re < 200$

$0 \leq Sc < 250$

$$Sh = \frac{k_c d_i}{D_{AB}} \quad (8)$$

$$Sc = \frac{\mu}{\rho D_{AB}} \quad (9)$$

$$Re = \frac{DV\rho}{\mu} \quad (10)$$

$$k_c = \frac{D_{AB} \left[ 2.0 + 0.6 \left( \frac{DV\rho}{\mu} \right)^{0.5} \left( \frac{\mu}{\rho D_{AB}} \right)^{0.33} \right]}{d_i} \quad (11)$$

$Sh$ : Sherwood number

$Re$  Reynolds number

$Sc$  Schmidt number

The mass transfer rate ( $N_A$ ) is measured relative to a set of axes fixed in space. The driving force is the difference between the concentration at the phase boundary,  $C_{As}$  (a solid surface or a fluid interface) and the concentration at some arbitrarily defined point in the fluid medium,  $C_A$ . The convective mass transfer coefficient ( $k_c$ ) is a function of geometry of the system and the velocity and properties of the fluid [11].

## B. Fuel Characterisation

The test results of fuel characterisations indicate that fuel blends compare very well with commercial diesel fuel. However the sulphur concentrations of blend are significantly higher than the allowable limit of 500 ppm as specified by the South African National Standards (SANS 342) fuel specifications. Properties such as density, total contamination, and water content and lower calorific values are within the fuel specification range. The viscosity of TDF-DF blend is lower than the minimum recommended limit of 2.3cSt. The flash

point of the diesel fuel is specified at 55°C or higher for safe storage and a consumption value below limit is observed on TDF-DF blend. Variations in physical properties from commercial diesel fuel may result in performance and emissions inconsistencies when used in conventional diesel engines.

TABLE I  
PHYSICAL PROPERTIES OF DF, TDF-DF (60:40)

Property	TDF-DF	DF
Density @ 20°C (kg/m <sup>3</sup> )	813	826
Viscosity @ 40°C (cSt)	1.5	2.3
Flash Point (°C)	43	56.21
Total Contamination (mg/kg)	4.624	3.31
Total Sulphur (ppm)	4,210	42
Water Content (%)	0.03	0.02
Gross Calorific Value (MJ/kg)	44.21	46.1
D <sub>AB</sub> (cm <sup>2</sup> /hr)* [14]		2.1

### C. Filter performance data

TABLE II  
TEST RESULTS FOR MICRO-MOLECULAR FILTRATION OF TDF-DIESEL BLEND

Fuel flow Φ(ml.min <sup>-1</sup> )	Total Sulphur C <sub>A</sub> (ppm)	Total Sulphur C <sub>AS</sub> (ppm)
144	4354	3408
145	4254	3514
146	4245	3578
145	4372	3595
<b>145</b>	<b>4307</b>	<b>3523</b>

Property	Unit Measure	Value
Fuel blend viscosity	μ(kg.m <sup>-1</sup> .s <sup>-1</sup> )	1.5×10 <sup>-3</sup>
Fuel blend density	ρ(kg.m <sup>-3</sup> )	813
Diffusivity	D <sub>AB</sub> (m <sup>2</sup> .s <sup>-1</sup> )	3.50×10 <sup>-6</sup>
Average flow rate	Φ(m <sup>3</sup> .s <sup>-1</sup> )	4.75×10 <sup>-6</sup>
Molecular filter media active area	κ(m <sup>2</sup> )	0.3967
Micro filter media active area	A(m <sup>2</sup> )	0.01424
Molecular media fuel velocity	v(m.s <sup>-1</sup> )	0.00454
Molecular media packing density	∂ <sub>p-molecular</sub> (kg.m <sup>-3</sup> )	844.04
Micro media packing density	∂ <sub>p-micro</sub> (kg.m <sup>-3</sup> )	168.99
Filter media housing tube inside diameter	D <sub>t</sub> (m)	0.04
Active length of media housing tube	l <sub>t</sub> (m)	0.1
Height of media housing bottom cone	h(m)	0.03
Average mass of porous membrane bead	m <sub>i</sub> (kg)	3.447×10 <sup>-5</sup>
Total mass of cotton fibres	m <sub>c</sub> (kg)	0.02336
Fuel residence time in molecular media	t(s)	22.1
Reynolds number	R <sub>e</sub> (-)	98.4
Schmidt number	Sc(-)	0.5
Sherwood number	Sh(-)	8.76
Initial total sulphur concentration	C <sub>A</sub> (%)	0.3523
Final total sulphur concentration	C <sub>AS</sub> (%)	0.4307
Mass transfer coefficient	k <sub>c</sub> (m.s <sup>-1</sup> )	9.58×10 <sup>-3</sup>
Mass transfer rate(adsorption rate)	N <sub>A</sub> (m <sup>3</sup> .s <sup>-1</sup> )	2.98×10 <sup>-4</sup>

The test results presented in Table II were calculated using (1) – (11) based on the average experimental tests data. The results show 18% reduction in total sulphur via liquid phase molecular filtration over molecular sieves. Liquid phase mass transfer rate was estimated at 2.98 x10<sup>-4</sup>m<sup>3</sup>.s based on the

average test data and empirical correlations. A detailed study on the individual diffusion rates of sulphurous compounds in the fuel will need to be investigated in order to draw conclusions on the adsorption characteristic of oxidative contaminants in the fuel.

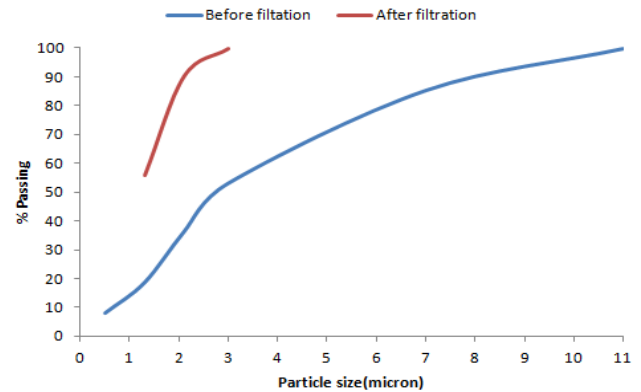


Fig. 6 Particle size distribution in the fuel before and after filtration

The size fraction in the fuel blend was analyzed using laser particle analyzer. The largest particle size in the fuel blend was detected at 11μm before filtration. The micro filter media used was capable of capturing up to 2.5μm in size as shown in Fig 6. The total suspended solids in the fuel blend was reduced by 78.2% to a final value of 4.624mg/kg as can be deduced from Table I compared to 3.31mg/kg in pure diesel fuel. This suggests that TDF contains more particle contaminants due to formation of asphaltenes. The particle size analysis results shows that 99.8% of ultra-fine particle contaminants are present in the filtered fuel blend with 50% below 1.3μm. Although the total suspended solids are within the allowable limits as per SANS 342, these fines carry a potential threat to the fuel injection system as they are likely to be bound together by asphaltenes and subsequently block the injector nozzles

## IV. CONCLUSIONS

The sulphur content in the fuel was reduced by 18% via a single pass molecular filtration using 13X molecular sieves with packing density of 844kg/m<sup>3</sup>. Adsorption of mercaptans and sulphur compounds occurs very rapidly over an active porous membrane layer. A significant amount of sulphur can be removed from the fuel stream at a rate of 2.98×10<sup>-4</sup>m<sup>3</sup>/s. The fuel properties of distilled fuel obtained at 250°C are nearly comparable to commercial diesel with high heating value and as well as low water content and total contamination. This research has also shown that particle contaminants of up to 2.5μm can be effectively captured by the packed cotton fibers at minimum packing density of 168kg/m<sup>3</sup>. This work has also that shown that distilled TDF cannot be used directly into compression ignition engines in its pure form due to its higher sulphur content, low viscosity and low flash point. A blend of 60 vol. % TDF and 40vol. % diesel fuel may be considered to

an extent whereby the overall viscosity and flash point of the blend fuel is at least 2.2cSt and 55°C respectively. The effect of packing density and voids between the membranes on the adsorption rate need to be investigated. Thermal reactivation of the membrane sieves for reuse and life span determination should be evaluated.

#### ACKNOWLEDGMENT

The authors are grateful to the National Research Foundation of South Africa, Departments of Mechanical and Chemical Engineering for supporting the research. The authors are also indebted to the Faculty of Engineering and the Built Environment of the University of Johannesburg for conference support.

#### REFERENCES

- [1] C. Roy, B. Labrecque, B. De Caumia, "Recycling of scrap tyres to oil and carbon black by vacuum pyrolysis", *Resources, Conservation and Recycling* vol. 4 (1990) 203–213.
- [2] A.M Cunliffe, and P.T Williams, "Composition of fuels derived from the batch pyrolysis of tyres," *Journal of Analytical and Applied Pyrolysis*, vol. 44, pp. 131-152, 1998.
- [3] T.J Pilusa, E. Muzenda, "Qualitative Analysis of Waste Rubber-Derived Oil as an Alternative Diesel Additive" *International Conference on Chemical and Environmental Engineering (ICCEE'2013)* April 15-16, 2013 Johannesburg, South Africa.
- [4] S. Murugan, M.C Ramaswamy, and G. Nagarayan, "A comparative Study on the performance, emissions and combustion studies of DI Engine using distilled tyre pyrolysis oil-diesel fuel blends," *Fuel*, vol. 87, pp. 2111-2121, 2008.
- [5] S. Murugan, M.C. Ramaswamy, G. Nagarajan, "Production of tyre pyrolysis oil from waste automobile tyres", *National Conference on Advances in Mechanical Engineering*, 2006, pp. 899–906.
- [6] G. Bhandodaya, G.Reddy, K.V Reddy, V.Ganesan, "Utilisation of non edible oil in diesel engine" *Proceedings of national conference in I.C engines*, 2001. p. 211–16.
- [7] K. Yoshiyuki, "Effects of fuel cetane number and aromatics on combustion process and emissions of a direct injection diesel engine". *JSAE* 2000, vol. 21 pp. 469–75.
- [8] V. Pradeep, R.P. Sharma, "Evaluation of performance, emission and combustion parameters of a CI engine fuelled with biodiesel from rubber seed oil and its blends", *SAE Paper No. 2005 26-353*, 2005, pp. 339–352.
- [9] T. J Pilusa, M Shukla, E. Muzenda, "Economic Assessment of Waste Tyres Pyrolysis Technology: A Case study for Gauteng Province, South Africa" Submitted to the International Conference on Advances in Engineering Sciences and Applied Mathematics (ICAESM' 2013), Nov 30 – Dec 1, 2013, Cape Town, South Africa.
- [10] T. J Pilusa, E. Muzenda, M Shukla, "Molecular Filtration of Rubber Derived Fuel" *2nd International Conference on Environment, Agriculture and Food Sciences (ICEAFS'2013)* August 25-26, 2013 Kuala Lumpur, Malaysia, *In International Conference Proceedings of the Planetary Scientific Research Centre*, pp.146 - 150, 2013.
- [11] R.B Bird, W.E Steward, E.N Lightfoot. "Transport Phenomena", Revised second edition New York: McGraw-Hill, 2006.
- [12] R. Lin, L.L Tavlarides, "Diffusion coefficients of diesel fuel and surrogate compounds in supercritical carbon dioxide" *The Journal of Supercritical Fluids*, vol. 52, Issue 1, 2010, pp 47–55
- [13] R.E Treybal. *Mass Transfer Operations*. 3<sup>rd</sup> Edition New York: McGraw-Hill