COMBUSTION OF VEGETABLE OIL DROPLETS

P. WIBULSWAS, K. SUPAPIMOL AND U. KEOWCHUNG

King Mongkut's Institute of Technology Thonburi
Bangmod, Bangkok 10140

ABSTRACT

Diesel oil in Thailand is imported from a neighbouring country or refined from inported petroleum. Several vegetable oils which are locally produced such as palm oil, rice bran oil, sun flower oil, soybean oil, and their derivatives, have potential to partially substitute diesel oil. However, a few technical barriers have to be overcome and the most suitable vegetable oil has to be identified.

A mass transfer theory based upon the Reynolds flow model is proposed to predict the combustion rates of vegetable oils and also used to predict the performance of a compression-ignition (C.I.) engine run on vegetable oils. The mass transfer conductance for the theory is deduced from natural and forced convection equations around a sphere and the mass transfer number is estimated from the heating value, mass fractions of the fuel and oxidant, etc.

With natural convection condition, the combustion rates of 2.5 and 5 cm diameter droplet models are predicted and tested for diesel oil, palm oil methyl ester, rice bran cooking oil, soybean oil and sunflower oil. Test results of 5 cm diameter model agreed fairly well with the predicted values. Deviations of experimental values from the corresponding predicted values are about 6 - 9%.

The mass transfer theory is applied to predict the performances of the C.I. engine. Based on forced convection equation on very small droplets, the power ratios of vegetable oils to diesel oil correspond fairly well to the predicted values. Because of the friction loss in the engine, correction factors based on engine speeds are derived to improve the predicted results.

Prediction on performances of C.I. engines needs refinement. Further studies should be conducted for other types of vegetable oil derivatives and for various blends between vegetable oils and diesel oil.

KEYWORDS

Combustion, compression-ignition, diesel compression-ignition, mass transfer, vegetable oils.

INTRODUCTION

Most developing countries have to import petroleum or its products to meet the energy demand in transportation. Large domestic supplies of vegetable oils such as palm oil coconut oil, rice bran oil, etc. in developing countries have potential to partially substitute petroleum products, especially diesel oil.

Several studies on the uses of vegetable oils in compression-ignition engines have been conducted. Akor et al [1] tested two types of air-cooled C.I. engines at 1200 rpm with palm kernel oil, ground nut oil and sunflower oil, and achieved good thermal efficiencies. Scharmer and Suttor [2] reported successful trials of raw rapeseed oil in a C.I. engines with pre-combustion chamber and fuel preheating. Yutiamco et al [3] used blends of coconut oil and palm oil with diesel oil on a 3- cylinder C.I. engine and found that at a speed of 1500 rpm, blends of palm oil and diesel yielded higher efficiencies than blends of coconut oil and diesel oil. The engine tended to knock if the vegetable oil content exceeded 80%. Wibulswas and Jung [4] predicted the combustion rates of droplets of palm kernel oil, coconut oil and diesel oil by means of a convective mass transfer theory and reported deviations of the predicted values from test results by 8.5 to 17.6%. Hassan and Mat [5] evaluated the performances of a single cylinder C.I. engine fueled by blends of palm oil methyl ester and diesel oil and found that better performances were obtained from the blends than diesel oil.

In this study, the convective mass transfer theory is extended to predict the output power of a single-cylinder C.I. engine fuelled by several types of vegetable oils.

THEORY

Prediction of Combustion Rate

A convective mass transfer theory based upon Reynolds flow model was developed by D.B. Spalding [6] and has been used in a previous study [4] and this study to predict the combustion rate of vegetable oil droplets. The theory can be expressed as

$$m'' = g^* \ln(1+B) \qquad (1)$$

where m'' = mass transfer flux, or in this study, combustion flux,
B = Spalding's transfer number,
g^* = mass transfer conductance derived from a suitable heat transfer equation.

Spalding's Transfer Number

For the combustion of a liquid fuel in the air, it is assumed that the fuel from a reservoir at t_O is first atomised into droplets and then vaporises from the surface of each droplet to burn with the air. It is further assumed that the surface temperature of the fuel droplet is at the boiling point, t_b of the fuel. Spalding's transfer number can be expressed as [4]

$$B = \frac{Cp_G (t_G - t_b) + m_{OX,G} H/r}{L + C_l (t_b - t_o)} \qquad (2)$$

where Cp_G = specific heat at constant pressure of the air,
t_G = bulk temperature of the air,
$m_{ox,G}$ = mass fraction of oxygen in the air,
H = lower heating value of the fuel,
r = stoichiometric ratio between oxygen and fuel,
L = latent heat of vaporisation of the fuel,
C_l = specific heat of the liquid fuel.

Mass Transfer Conductance

Based upon the heat transfer equation for forced convection on a sphere [7], the mass transfer conductance for the combustion of a fuel droplet in the air can be expressed as [4]

$$g^* = (\mu d.Sc)(2+0.6\, Re^{0.50} Sc^{0.333}) \qquad (3)$$

where μ = dynamic viscosity of the air,
d = diameter of the fuel droplet,

Sc = Schmidt number of the fuel vapour in the air,

Re = Reynolds number based on the droplet diameter.

If the droplet combustion occurs in free convection regime, the mass transfer conductance can be expressed as [7]

$$g^* = (\mu/d.Sc)\ (2+0.6\ Gr^{0.25}Sc^{0.333}) \quad \text{(4)}$$

where Gr = Grashof number based upon the droplet diameter.

Prediction of Output Power of C.I. Engine

In this study, an attempt is made to predict the output power of a C.I. engine from the mass transfer of single fuel droplet discussed in the preceding sections.

The output power, P from a C.l. engine depends upon the fuel consumption rate, **m** and the heating value of the fuel, **H** and can be expressed as

$$P = \text{constant}.\ H.m$$

The output power ratio between the vegetable oil and diesel oil used in the same engine,

$$\frac{P_v}{P_d} = \frac{H_v.m_v}{H_d.m_d} \quad \text{(5)}$$

where subscripts **v** and **d** denote vegetable oil and diesel oil respectively. As fuel droplets from the injection nozzle of a C.l. engine have very small diameters, the average Reynolds number can also be assumed very small. Equation [3] is therefore simplified into

$$g^* = 2\ \mu\ /dSc$$

The combustion flux -from Equation (1) can be expressed as

$$m'' = [2\ \mu\ \ln(1+B)]/dSc$$

The fuel consumption rate, **m** can be expressed in terms of droplet diameter, **d** and number of droplets, **n** injected per second as

$$m = n.\pi\ d^2.\ m''$$

$$= [n\pi d.2\ \mu \ln(1+B)]/Sc$$

For the same fuel injection rates into the same C.l. engine, **d** and **n** can be assumed the same -for both vegetable oil and diesel oil. Substitute the above equation in Equation [5],

$$\frac{P_v}{P_d} = \frac{H_v\ Sc_d\ \ln(1+B_v)}{H_d\ Sc_v\ \ln(1+B_d)} \quad \text{(6)}$$

As the loss of power in a real engine will vary as the engine speed, N, it is proposed that the actual output power,

$$P_a = k\ P/N^a \quad \text{(7)}$$

where P = predicted power

k,a = constants.

The actual power ratio between the vegetable oil and diesel oil is derived from Equations (6) and (7) as

$$\frac{P_{v,a}}{P_{d,a}} = \frac{H_v\ Sc_d\ \ln(1+B_v)}{H_d\ Sc_v\ \ln(1+B_d)} \left(\frac{N_d}{N_v}\right)^a \quad \text{(8)}$$

Finally, the index, a, of the speed factor, N_d/N_V, can be determined by dividing Equation (8) by Equation (6).

$$\frac{P_{v,a}/P_{d,a}}{P_v/P_d} = \left(\frac{N_d}{N_v}\right)^a$$

$$\log\left(\frac{P_{v,a}/P_{d,a}}{P_v/P_d}\right) = a\log\left(\frac{N_d}{N_v}\right) \quad \text{(9)}$$

From the above equation, 'a' is the slope of the graph

$$\log\left(\frac{P_{v,a}/P_{d,a}}{P_v/P_d}\right) \text{v.s.} \log\left(\frac{N_d}{N_v}\right)$$

PROPERTIES OF VEGETABLE OILS

Several properties of vegetable oils are required for the prediction of their combustion rates. These properties may be determined from the following empirical folmulae

Specific gravity, **d,** [8] $= 0.9244 - 0.00067\,t$
where t = temperature of the oil, in C.

Latent heat of vaporaization, L, in kJ/kg [8]

$= (108-0.162\,t_b)\,2.33/d$

Specific heat of the liquid oil, C_l, in kJ/kg.C, [9]

$= 1.97 + 0.00305\,t$

Schmidt of the oil vapour in the air, Sc [10]

$= 0.145\,M^{0.556}$

where M = apparent molecular weight of the oil.

As a vegetable oil comprises several saturated and unsaturated fatty acids, the oil therefore boils through a range of temperatures. In this study, it is suggested that the mean boiling point, t_b is determined from the variation of the boiling temperatures with time.

Table 1 Physical Properties of Vegetable Oil.

	Palm Oil Methyl Ester	Rice Bran Oil	Soybean Oil	Sunflower Oil
Specific gravity	0.880	0.920	0.920	0.922
Mean boiling point, C	212	269	261	265
Latent heat, kJ/kg	195.0	163.1	166.4	164.4
HHV, MJ/kg	38.28	40.41	38.47	38.56
Molecular Weight	283	280	278	279
Sc	3.35	3.33	3.31	3.32

Table 2 Ultimate Analyses of Vegetable Oils, in %.

	Palm Oil Methyl Ester	Rice Bran Oil	Soybean Oil	Sunflower Oil
Carbon	75.1	78.7	78.3	79.9
Hydrogen	13.6	12.7	12.1	12.9
Oxygen	11.1	8.4	9.3	6.6
Nitrogen	0.03	0.02	0.05	0.06
Sulphur	0.21	0.15	0.22	0.55

TEST EQUIPMENT AND PROCEDURES

Droplet Combustion Tests

The apparatus consisted of a brass sphere with a diameter of 50 or 25 mm. The fuel flowed over the surface of the sphere from a constant-head vessel with an over-flow tube to maintain a constant flow rate. The vessel was continuously replenished by the fuel from another fuel tank, see Fig.1

To start a test, the thin film of oil on the sphere surface was heated by a bunsen burner until the fuel reached the flash point and the flame was maintained. Four types of vegetable oils, namely palm oil methyl ester, soybean, sunflower and rice bran oils, were tested.

Engine Tests

A four-stroke single-cylinder diesel engine was used to test the vegetable oils at various speeds. The output power from the engine was determined by a hydraulic dynamometer. Other measuring equipment were fuel flow meter and tachometer, see Fig. 2. The engine was first run at no load to obtain the maximum speed. The load was gradually increased in steps and the corresponding power was determined until the engine stopped.

RESULTS AND DISCUSSIONS

Combustion rates of a single droplet were predicted for the palm oil methyl ester, soybean, sunflower and rice bran oil. Comparisons of the predicted and measured combustion rates of the vegetable oils from 50 mm. sphere were shown in Fig.3. The measured values were 6-9% higher than predicted ones. Deviations might be contributed by inaccuracies of physical properties of oils, Schmidt numbers, unburned tars on the sphere surface, etc.

The predicted and tested power ratios of vegetable oil to diesel oil, P_v/P_d, were compared in Fig. 4 for maximum output power. Without correction by a speed factor, $(N_d/N_v)^a$ deviations between 15-20% can be seen, as the friction losses at different speeds have not been accounted for.

Fig.5 shows a plot between $\log(N_d/N_v)$ v.s.$\log(P_{v,a}/P_{d,a})/(P_v/P_d)$. Indices, a, are the slopes at various (N_d/N_v). The average speed factor of 1.28 was obtained for maximum output power.

Comparisons of the predicted and tested power ratios with speed factor correction are shown in Fig.6. Deviations between the predicted and tested values are now reduced to $\pm$ 5%

CONCLUSIONS AND RECOMMENDATIONS

Combustion rates of vetgetable oil droplets can be predicted by application of Spalding's convective mass transfer theory with reasonable accuracy. Based upon the performance of an I.C. engine run on diesel oil under similar condition, the theory can be extended to predict the output power of I.C. engine run on various types of vegetable oils. Accuracy of the prediction improves considerably when speed factor correction is incorporated.

A further study should be conducted on the refinement of prediction method for the preformance of a diesel engine run on vegetable oils. Combustion of other vegetable oil derivatives and blends of between a vegetable oil and diesel oil should also be studied.

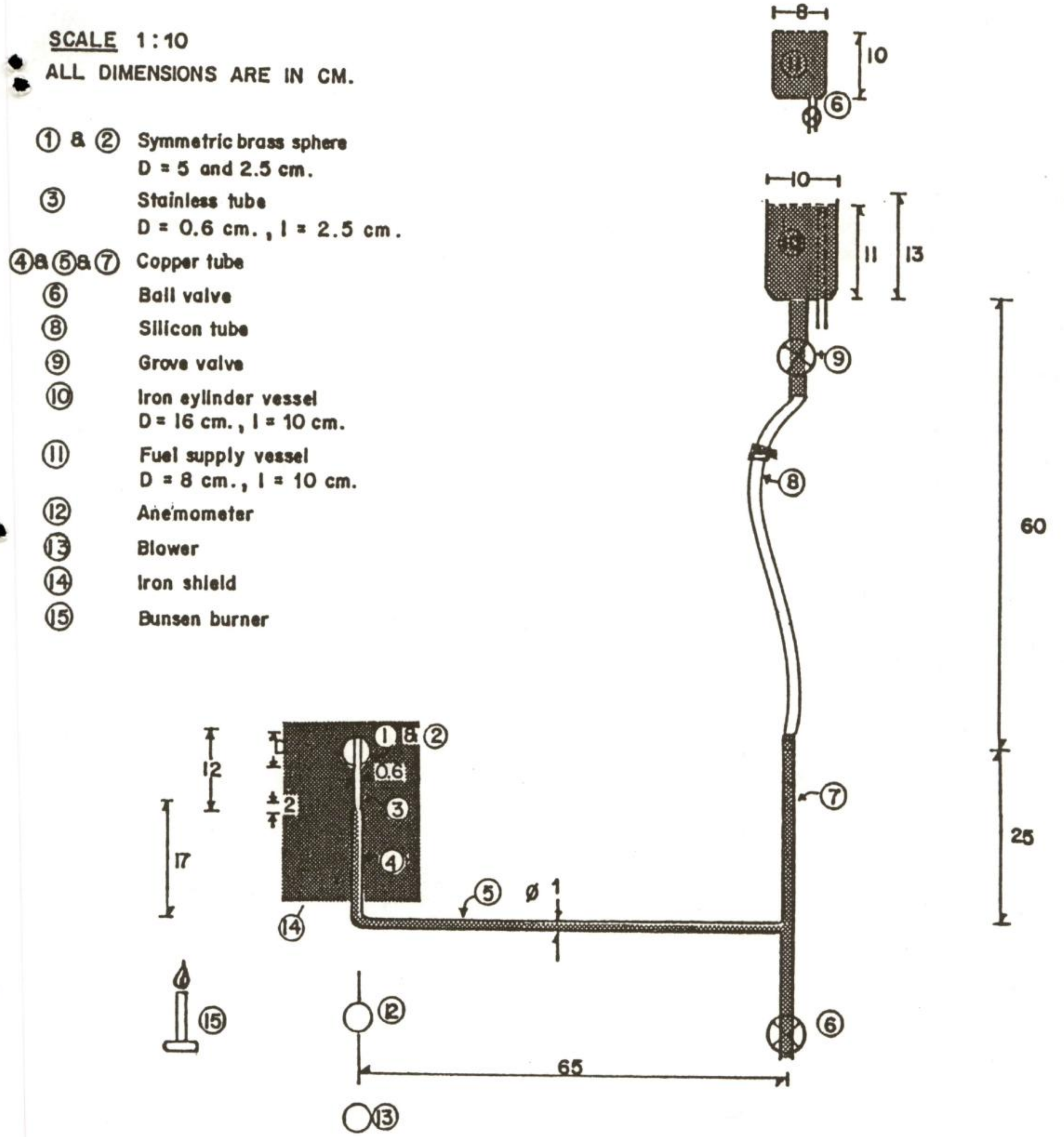

Figure 1 Schematic diagram of single-droplet combustion apparatus.

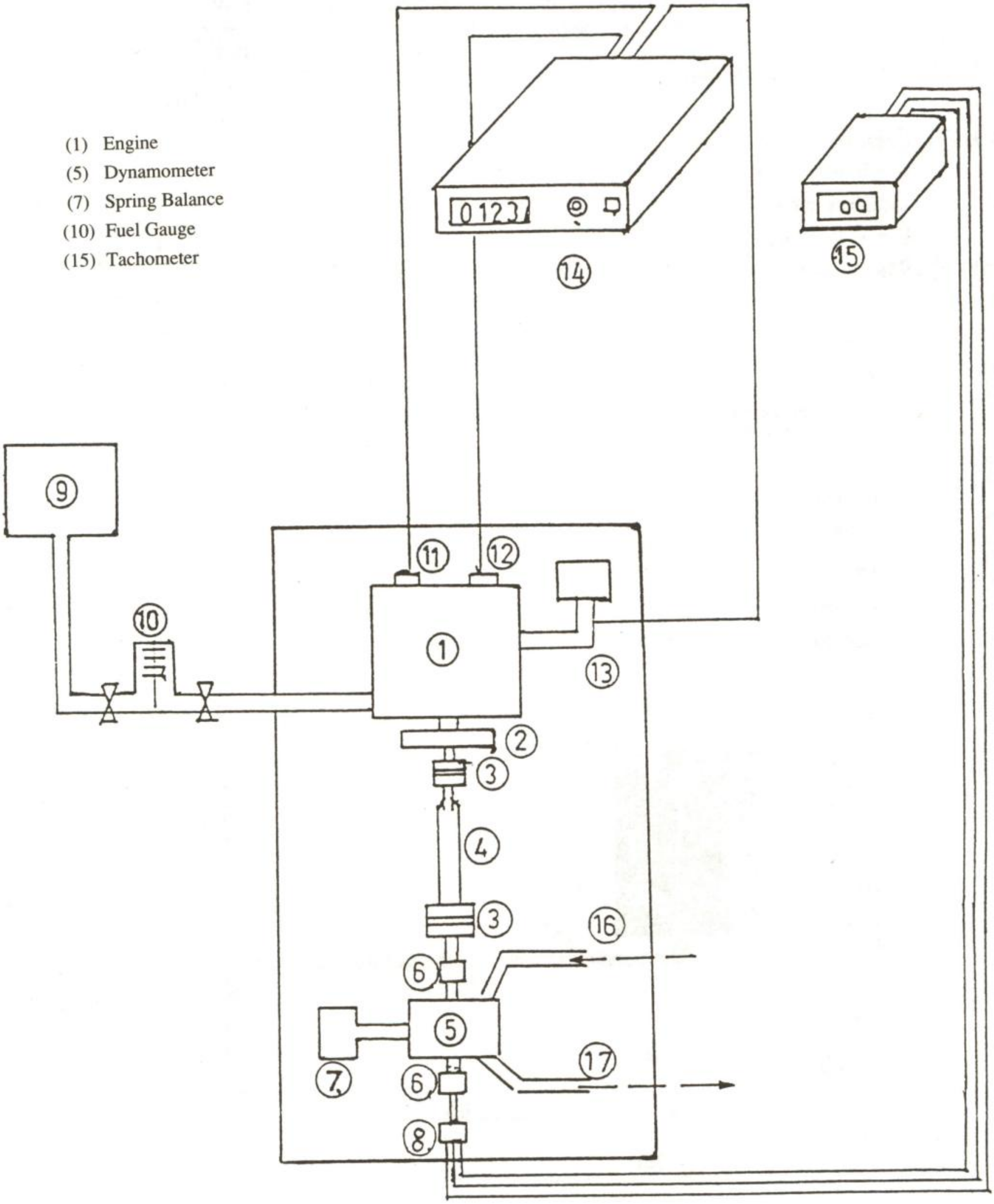

Figure 2 Diagram of Engine Test Facilities.

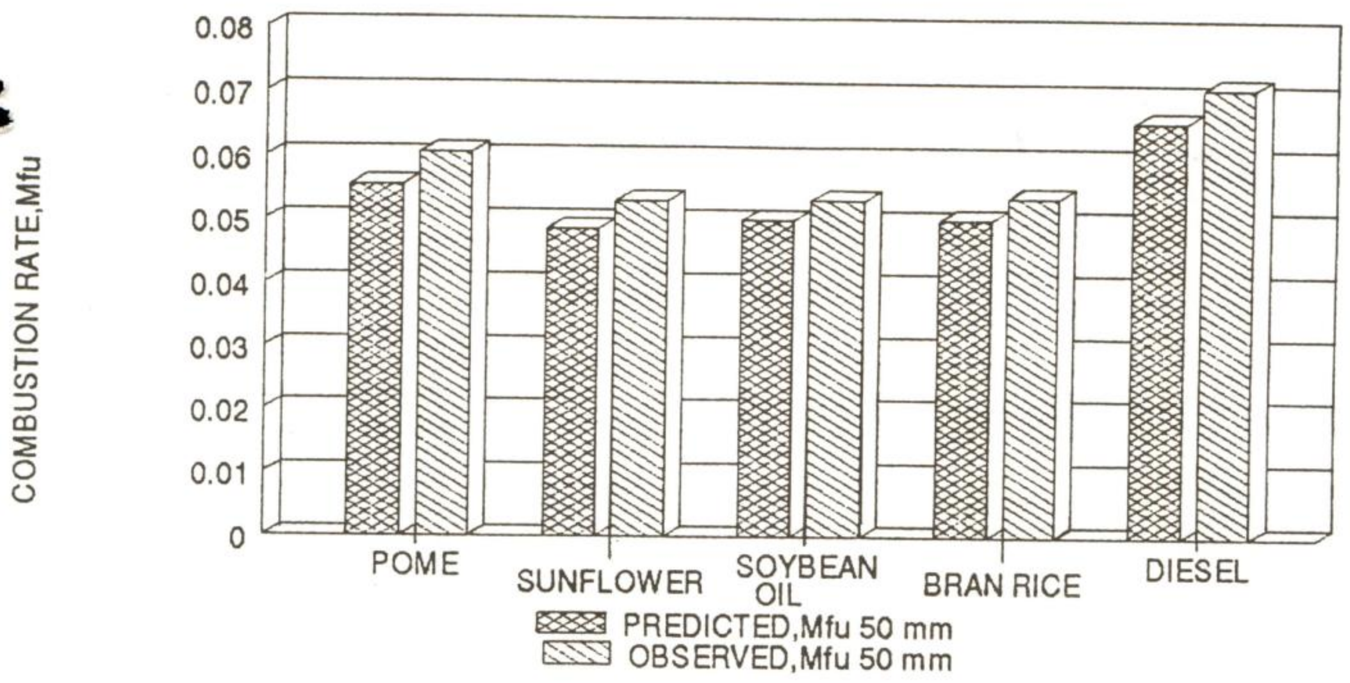

Figure 3 Comparison between predicted and measured combustion rate on 50 mm sphere.

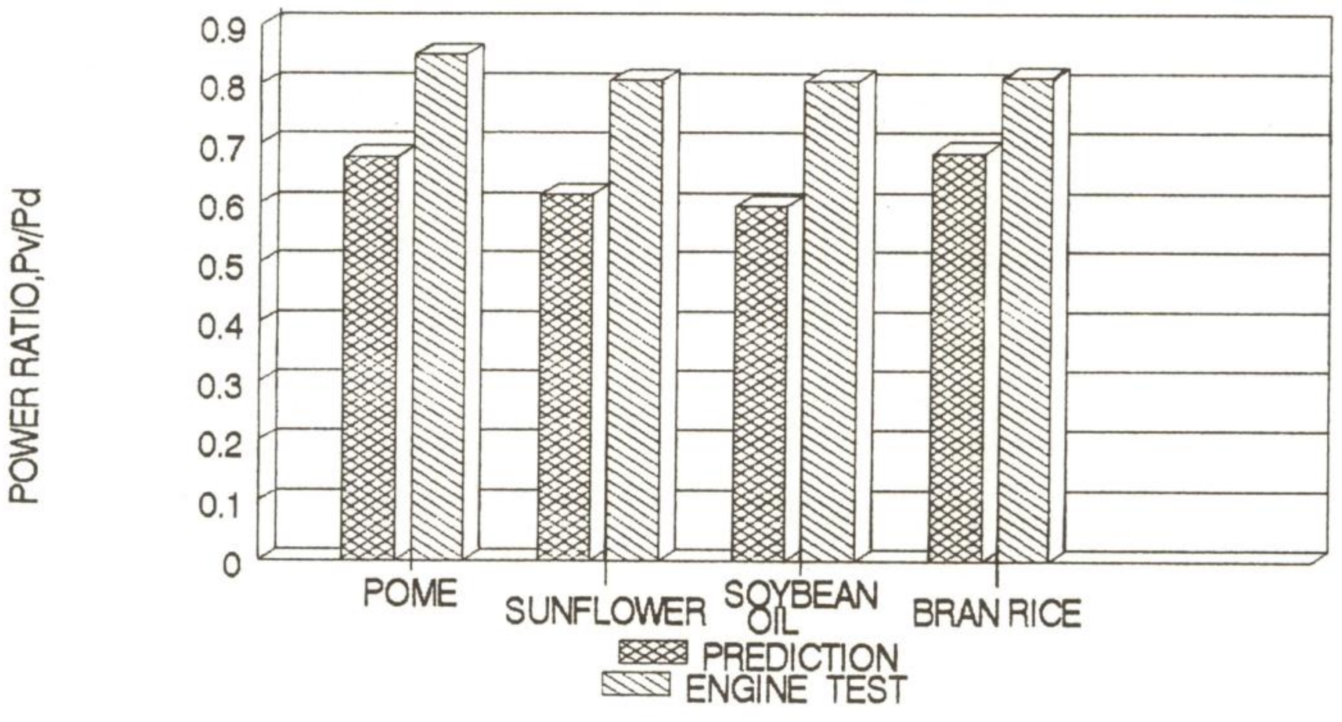

Figure 4 Comparison between predicted and measured power ratios of vegetable oils to diesel oil at maximum output power.

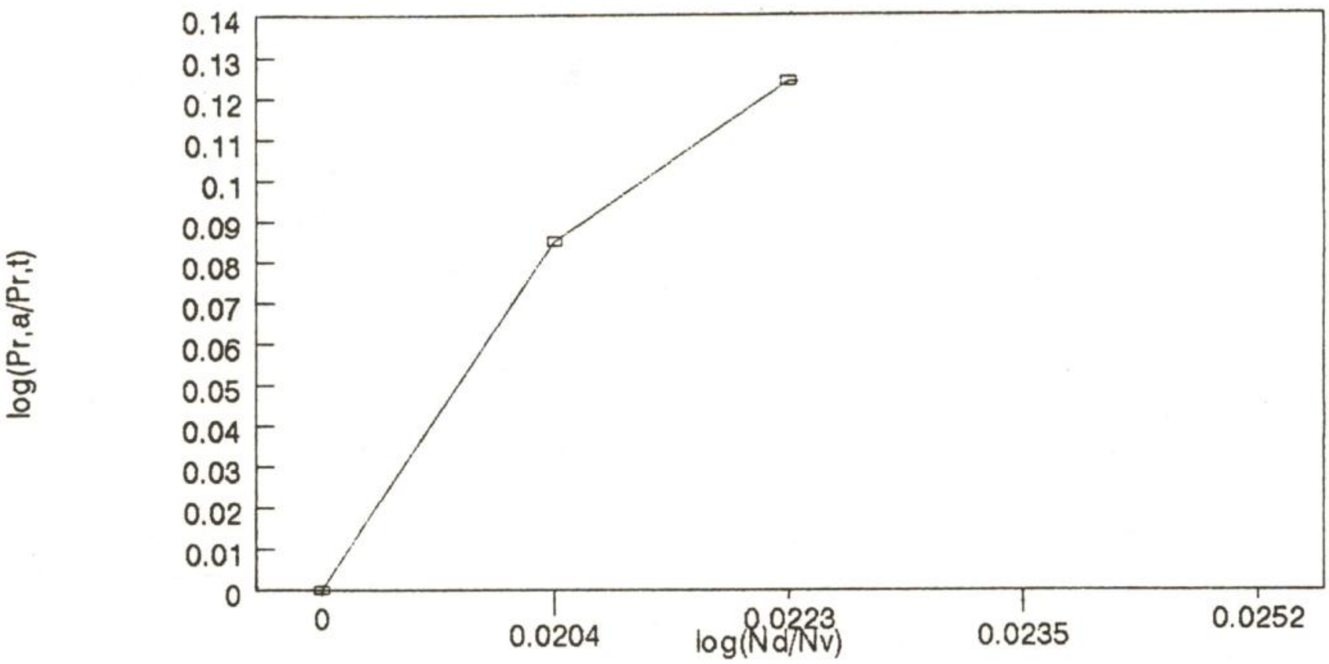

Figure 5 Determination of indices for speed factor at maximum output power.

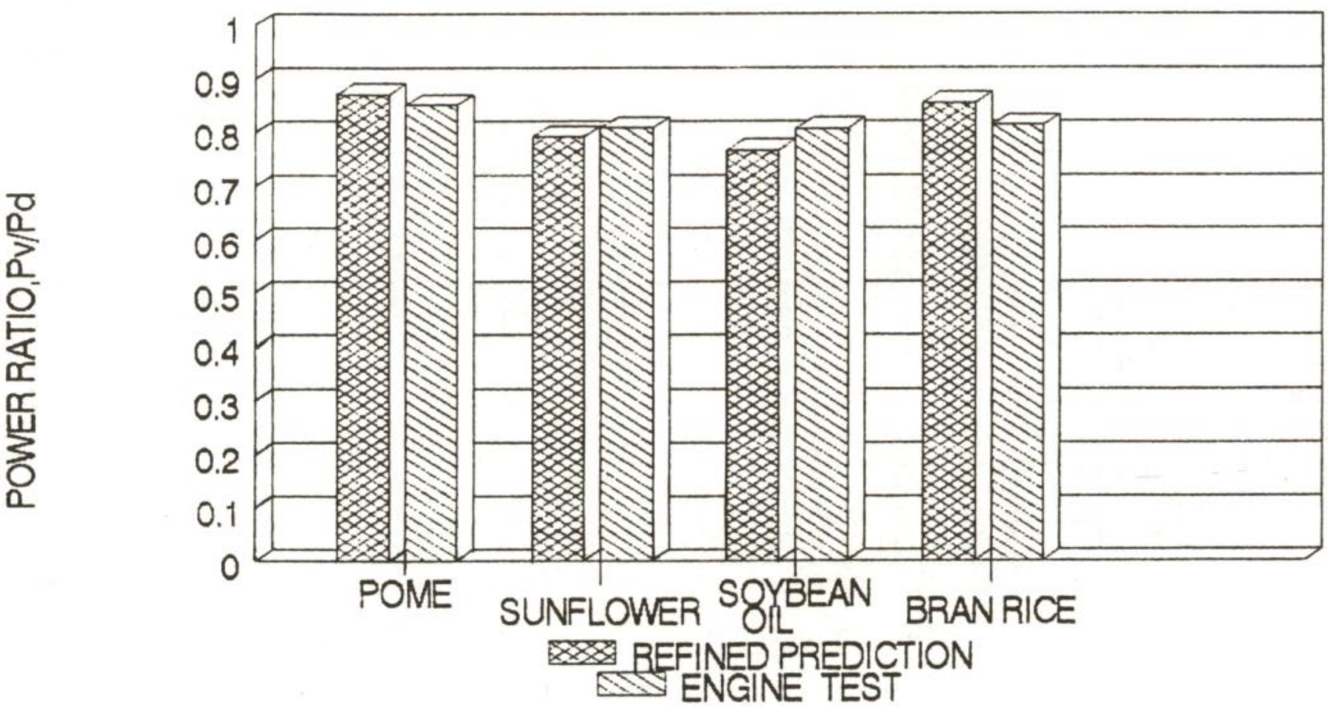

Figure 6 Comparison between predicted and measured power ratios of vegetable oils to diesel oil at maximum power, with speed factor correction.

REFERENCES

1. Akor A.J., Chancellor W.J. and Raubach N., "The potential of palm oil as a motor fuel", Transaction of ASEAE, Vol. 26, No. 1, 1983, pp. 23-28.
2. Scharmel K. and Suttor K.H., "On-farm conversion of rape seed in liquid fuel, solid fuel and high protein feed", Advances in Solar Energy Technology, Vol. 3, Pergamon, 1988, pp. 2264-68.
3. Yutiamco A., Sangbangpla P. and Wibu lswas P., "C.I. engine operation on coconut and palm oils", Proc. of ASEAN Conf. on Energy from Biomass, ASEAN Working Group on Non Conventional Energy Research, Pcnang, 1986, pp. 106-117.
4. Wibulswas P. and Jung O.,"Combustion of biomass liquid fuel", ASEAN J. on Science and Technology, Vol. 6, No. 1, 1989, pp. 67-79.
5. Hassan M.H. and Mat S., "Performance evaluation of palm oil-diesel blend in small engine", J.Energy, Heat and Mass Transfer, Vol. 13, No. 3, 1991, pp. 125-134.
6. Spalding D.B., "Combustion and mass transfer", Pergamon Press, Oxford, 1979, pp. 125-144.
7. Ranz W. and Marshall W., "Evaporation from drops", Chemical Engineering Progress, Vol. 48, 1952, pp. 141-180.
8. Chong C.L., Palm Oil Report, Vol. 58, Palm Oil Research Institute of Malaysia, 1983.
9. Timms R. E., "Physical properties of oil and mixtures of oils", J. of American Oil Chemists Society, Vol. 62, No. 2, pp. 241-249.
10. Spalding D.B., "Convective Mass Transfer", Edward Arnold., 1963, pp. 141.

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