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THE BEHAVIOUR OF STARTING FUELS IN DIESEL ENGINES WHEN INJECTED INTO THE INDUCTION PIPE

SUMMARY: When starting fuels were investigated at low temperatures, it was found that vapour pressure and cetane number both affect the starting behaviour. For the most favourable result the fuel should possess high cetane number and high vapour pressure (corresponding to low boiling point). For practical use with induction injection the following are most suitable, in this order: Ethyl-iso-propyl-ether, Di-ethyl ether, Di-iso-propyl-ether, and Di-n-propyl ether. Less suitable are Methyl-n-butyl ether, Ethyl-n-butyl ether, and methyl-iso-butyl ether.

Object of the tests.

The tests, described in the short report No. 321, on the starting behaviour of starting fuels at normal temperatures, were to be extended to temperatures below 0°C. The possibility was to be examined of using the fuels in practice.

Test Method

The tests were carried out in the cold chamber on the I.G. test Diesel. As in the tests described in report No. 321, the starting fuel was injected into the bend of the induction manifold during the induction stroke (30° before top dead centre) by an engine operated injection pump. This ensured that the volume of fuel in the cylinder was constant for every stroke (see Fig.1)

Since in the course of the tests the starting fuel was always injected into the induction pipe, the fuels under investigation will hereinafter be known as A.S. fuel (to distinguish them from A.Z. fuels, which are injected into the cylinder). In order to intensify the starting conditions, the engine was motored at 100 rpm, through a self-disengaging coupling to prevent the gears braking the engine at the instant of starting. A Bosch nozzle injecting with a spray angle of 20° (DV 2313/2) was used to atomise the A.S. fuel. The incidence of ignition during starting was observed through a window in the cylinder head.

Fig. 1 shows the vapour pressure curves of the fuels investigated. The individual vapour pressure curves are arranged according to the rise in the boiling point (see also short report No.326).

The following were investigated:

1. Di-ethyl ether.
2. Ethyl-iso-propyl ether
3. Methyl-iso-propyl ether
4. Di-iso-propyl ether
5. Di-n-propylether
6. Ethyl-n-butyl ether.
7. Methyl-n-butyl ether
8. Di-n-butyl ether.
9. Methyl iso butyl ether.
10. Methyl-sec-butyl ether
11. 2-methyl pentane
12. Tetra-hydro-furane
13. Acetal
14. Methyl-ethyl-glycol ether
15. Di-ethyl glycol ether
16. Di-allyl-ether
17. Di-allyl-glycol
18. Di-iso-amyl-ether
19. Normal gasoline
20. Supraline
21. Petroleum ether.

The fuel data given on plates 2-5 are for the individual A.S. fuels at reduced vapour pressure at -20°C. The data in the third column from the end, headed 152/Z, are explained by the following calculation of the fuel-air ratio of vapours:-

The number of mols. of oxygen required for the combustion of one mol. of the combination CnHpOg is:-

$$Z = n + \frac{p}{4} - \frac{g}{2}$$

Therefore to burn 1 mol. of O_2 or air, $\frac{1}{z}$ or $\frac{0.21}{Z}$ mols of fuel are necessary. In a mixture of fuel and air, the actual fuel content is in accordance with the partial pressures $\frac{pt}{760}$ mol (pt = vapour pressure at t°), if the pressure in the induction tube is 760 mm. The fuel/air ratio is then

$$\lambda = \frac{0.21}{Z.\frac{pt}{760}} = \frac{152}{Z.pt}$$

To attain the theoretical fuel air ratio $\lambda = 1$, a minimum vapour pressure of $p = \frac{152}{Z}$ is required. In the third column from the end on pp. 2-5 this value is given, as is also that for $\lambda = 1.5$ for the individual substances in mm. Hg, with below them the temperature, taken from the vapour pressure tables (Plate 1) at which the calculated minimum vapour pressure prevails. Thus, according to this calculation a fuel/air ratio of $\lambda = 1$ can still occur with die-ethyl ether at -36°, whereas with ethyl-iso-propyl-ether, which is next in order, this is not possible below -27°. The fuels investigated were most of them laboratory products, only available in small volume. Therefore in the case of some of the fuels only a few tests could be taken.

Results of Tests

The compression at which ignition occurred was determined at various temperatures, with 160 mm³/stroke of A.S. fuel injected into the induction pipe. This is about the volume of A.S. fuel which is necessary for the theoretical combustion of the air inducted at $\lambda = 1$. The engine was motored for these tests at 100 rpm. without injection of the main fuel. The results of this series of tests are shown in the last two columns of the table, plates 2 to 5, the lower compression limit being shown under E, with the appropriate temperature on the right. Plate 6 shows these values in the form of a graph. Figs. 1 and 2 show that the limit curves (lower compression limit as a function of temperature) have essentially the same course: as the temperature falls, a higher compression is necessary for ignition. As the vapour pressure falls the curves generally become higher. An exception is ethyl-iso-propyl-ether, which, despite lower vapour pressure requires considerably less compression than the ordinary di-ethyl-ether. In spite of their good vapour pressure, methyl pentane and tetra hydro furane are bad starters, because, as shown below, they do not fulfil the secondary requirement of a good cetane number. On the other hand, di-iso-propyl-ether, in spite of its very low cetane number and a less favourable vapour pressure than the two latter substances, has a good starting capacity.

An attempt was also made to establish whether, if various A.S. fuels are mixed there is an unexpected effect. Therefore, several mixtures of di-ethyl ether of which there were larger quantities available with higher boiling A.S. fuels were tested under the above conditions. It appeared however, that the mixtures merely raised the compression limit according to the proportion of higher boiling fuel which was added.

With di-ethyl-ether and ethyl-iso-propylether, the two fuels which had the lowest boiling points, a rise in compression, under the above conditions caused spontaneous combustion in the cylinder above a certain limit, the flame very often striking back into the induction pipe. Ignition occurred so early that the fuel was burnt before compression was over. As a result the engine did not start, or stopped after several revolutions. The course of those "upper" compression limits is shown on Fig.7 for both fuels, together with the lower limit. Thus, between two compressions there is a region in which, if ignition occurs with certainty, the engine is certain to start. With the higher-boiling A.S. fuels this phenomenon was only observed at higher temperatures and very high compression (ε = 19-20) The danger that the upper limit will be exceeded if the A.S. fuel used is of too high a grade can be countered by regulating the A.S. fuel.

A second series of tests was made to determine the volume of A.S. fuel required to cause ignition at constant compression (ε = 16) and room temperature (-20°). Finally, in a third series of tests, Diesel fuel was injected into the combustion chamber and A.S. fuel into the induction pipe, and the pressure was determined at which ignition occurred at constant volume and constant room temperature.

Fig. 8 shows the results of those tests in decreasing order of vapour pressure. The highest possible volume of A.S. fuel injected in the second series of tests was 270 mm³/stroke. (The tests in which ignition did not occur at this volume are marked with a broken line). In the third series of tests, the engine started on gas oil alone at a compression of ε = 20, so that here the A.S. fuel had no effect. It may be seen that as the vapour pressure falls the starting capacity runs parallel with it. Methyl pentane and tetra-hydro-furane are again exceptions. Ignition was only observed below a vapour pressure of 6 mm Hg at -20° with Di-n-butylether. The temperatures t (λ=1) which the calculation on page 2 shows to be those at which λ= 1 can still be attained are entered on the right side of plate 8. But as the examples of methyl pentane and tetra-hydro furane show, the test results do not agree with the calculation, that is to say, the degree of saturation of the fuel air mixture does not of itself determine the start behaviour.

To establish a relationship between vapour pressure and cetane number as regards starting behaviour, the results of the second and third series of tests were entered as functions of vapour pressure in plate 9. If we now connect the test points of those A.S. fuels which have roughly the same cetane number (cetane number near the test points), the result is a curve which shows the lower limit of ignition of this range of cetane numbers as a function of vapour pressure. Those fuels which do not cause ignition at the maximum injection volume, either have an adequate cetane number with inadequate vapour pressure (Di-n-butyl ether and di-allyl ether), or have adequate vapour pressure and too low a cetane number (methyl pentane, tetra-hydro-furane, and acetal). Di-iso-propyl ether is an exception to this general rule, which in spite of an unsatisfactory cetane number (13) causes ignition.

If the results of the third series of tests (gas oil + A.S. fuel) are entered in the same way in Fig.2, it is impossible to establish a law. Owing to the fact that the Diesel fuel is injected into the combustion chamber simultaneously the variations become too great. It is also noticeable here that Di-iso-propyl ether has a poor cetane number, and yet a low compression limit.

Normal gasoline (boiling point 65-75), petroleum ether and supraline were also investigated for purposes of comparison (see plates 4 and 5). These fuels, which are much used as starting agents in practice, had less effect than the A.S. fuels investigated. It was only possible to obtain results with normal gasoline in the first series of tests (see plate 6 Fig. 2).

The following table gives an idea of the results:-

1st. Test Series.

Showing ε at various temperatures A.S. volume 160 mm^3/stroke.
Results plotted on plates 6 and 7.

Order of rating:-	ε-20°	Boiling Point °C	Cetane Number	Vapour Pressure mm Hg @ -20°
Ethyl-iso-propyl ether.	9	53	92	27
Di-ethyl ether	13	36	110	36
Di-isopropyl ether	16	69	13	14.5
Methyl-iso-butyl-ether	19	59	50	24
Normal gasoline	20	65-75	45	15

2nd Test Series.

Showing A. S. volume ε at = 16
t = -20°

Results plotted on plates 8 and 9.

Order of rating:-	A.S. mm^3/stroke	Boiling Point °C	Cetane Number	Vapour pressure mm Hg. - 20°C
Diethylether	50	36	110	75
Ethyl isopropyl ether	80	53	92	27
Di-normal propyl-ether	150	91	113	7.7
Methyl normal butyl ether	150	70	84	13
Di-isopropylether	200	69	13	14.5
Ethyl-n-butylether	240	92	98	6

3rd Test Series

Gives ε under conditions t = 20°, A.S = 160 mm^3/stroke
Gas oil 140 mm^3/stroke

Results plotted on plates 8 and 9.

Order of Rating:-	ε	Sp.°C	Cetane No.	Vapour Pressure - 20.
Ethyl isopropylether	9.5	53	92	27
Ethyl normal butyl ether	11.0	92	98	6
Diethylether	12.5	36	110	75
Di-normal propylether	13.0	91	113	7.7
Di-isopropylether	14.0	69	13	14.5
Di-n-butylether	16.0	141	125	2.2

As far as such tests allow us to draw conclusions, the following fuels are suitable for use as starting aids with induction pipe injection.

	Boiling Point.	Cetane Number	Vapour Pressure in mm Hg @ -20°
Ethyl iso propyl ether	53	92	27
Di ethyl ether	36	110	75
Di iso propyl ether	69	13	14.5
Di-normal propyl ether	91	113	7.7
also:			
Methyl normal butyl ether	70	84	13
Ethyl normal butyl ether	92	98	6
Methyl iso butyl ether	59	50	24

The tests showed that the cetane number and the vapour pressure both considerably affect the start behaviour of starting fuels under induction-pipe injection, but that the inner structure of a fuel is also a factor, as the example of di-iso-propyl ether shows.

Fig. 1 Vapour pressure curves.

Fig. 2 Starting tests.

R-material	Formula	O.N.	C.N.	Vapour Press. @ -22°C mm.	Boiling Pt. °C	Air Required m^3/Kg-g/l.	Calorific value	(1) 152/Z	Ignition at (1) ε	°C
Di-ethyl ether	$C_4H_{10}O$	0	110	75	36	9.41 0.1063 (2)	8110	λ = 1 25.3 mm ~ -36° λ = 1.5 16.9 mm ~ -43°	16 11.5 10 10 10	-25 -18 -12 -10 - 9
Ethyl-iso-propylether	$C_5H_{12}O$	45*	92	27	53	9.9 0.101	8200	λ = 1 20.3 mm ~ -27° λ = 1.5 13.5 mm ~ -32°	14 10 9 9 8 8 7.0	-26 -25 -22 -20 -18 -16 -14
Methyl-sec-butyl ether	$C_5H_{12}O$	43*	60	3) 24	60°	9.9 0.101		λ =1 20.3 mm ~ -24° λ =1.5 13.5 mm ~ -28°	16 12	-25 -15
2-methyl pentane	C_6H_{14}	70.5	33.5	24.5	62			λ=1 16 mm ~-27° λ =1.5 10.65 mm ~-33°	- 19 19 18 17 15	-23 -20 -17 -14 -12 -9

Figure 2 continued overleaf.

Figure 2 - Starting Tests continued.

R-material	Formula	O.N.	C.N.	Vapour Press. @ -22°C mm.	Boiling Pt. °C	Air required m^3/Kg- g/l.	Calorific valuc	$\frac{152}{Z}$ (1)	Ignition at ε	°C (1)
Methyl-iso-butylether	$C_5H_{12}O$	28.5*	50	24	59	9.9 0.101	8425	λ = 1 20.3 mm ~ -24° λ = 1.5 13.5 mm ~ -28°	20 18	-25 -16
Tetra-hydro-furane	C_4H_8O	25	30	17	67	8.9 0.113		λ = 1 27.6 mm ~ -14° λ = 1.5 19.6 mm ~ -19°	- 18	-18 -16
Methyl-iso-propylether	$C_4H_{10}O$	42.5*	40-45	15.5	32°	9.41 0.106		λ = 1 25.3 mm ~ -12° λ = 1.5 16.9 mm ~ -19°	16 11	-25 -17

* Mixed O.N. with 75% I.G.9, O.N. 44.6

1) See test
2) g/l = g fuel necessary for burning 1 ltr. of air
3) as methyl iso butylether

Fig. 3 - Starting Tests.

R-Material	Formula	O.N.	C.N.	Vapour Press. @ -22°C mm.	Boiling Pt. °C	Air required m^3/Kg - g/l.	Calorific value	152/Z (1)	Ignition at ε	°C (1)
Di-iso-propyl-ether	$C_6H_{14}O$	100	13	14.5	69	10.23 0.098		λ = 1 16.9 mm ~ -18° λ = 1.5 11.25 mm ~ -27°	- 15 13.5 13	-25 -18 -17 -10
Methyl-n-Butylether	$C_5H_{12}O$	28.5*	84	13	70	9.9 0.101		λ = 1 20.3 mm ~ -24° λ = 1.5 13.5 mm ~ -28°	- 16	-20 -18
Di-n-propyl ether	$C_6H_{14}O$	29.5*	113	7.7	91	10.23 0.0978	8760	λ = 1 16.9 mm ~ - 6° λ = 1.5 11.25 mm ~ -14°	- 20 12 9	-25 -17 -13 - 9
Ethyl-n-Butylether	$C_6H_{14}O$	20.5*	98	6	92	10.23 0.0978	8760	λ = 1 16.9 mm ~ -14 λ = 1.5 11.25 mm ~ -11	- 15 9	-25 -15 -10
Acetal	$C_6H_{14}O_2$	<0*	45	6	102	8.59 0.1163	7140	λ = 1 17.9 mm +70 λ = 1.5 11.5 mm - 2	-	-17
Methyl-ethyl glycol ether	$C_5H_{12}O$		125	5	102	9.9 0.101	7025	λ = 1 20.3 mm ~ + 7 λ = 1.5 13.5 mm ~ - 1°	18	-10
Diallyl ether	$C_6H_{10}O$	39.7**	77	3.4	98	9.47 0.105	7860	λ = 1 19 mm ~ +6° λ = 1.5 12.65 mm ~ -10°	-	-16
Di-n-Butyl-ether	$C_8H_{18}O$		125	2.2	141	10.7 0.093	9130	λ = 1 12.65 mm ~ +23.5° λ = 1.5 8.45 mm ~ +12°	-	-10

* Mixed O.N. with 75% I.G.9; O.N.44.6
** Mixed O.N. with 75% I.G.7; O.N.43.8

1) See Text.

Figure 4 - Starting Tests

R-Material	Formula	O.N.	C.N.	Vapour Press. @ -22°C mm.	Boiling Pt. °C	Air required m^3/Kg-g/l.	Calorific value	(1) $\frac{152}{Z}$	(1) Ignition at °C	
									ε	°C
Di-ethyl glycolether	$C_6H_{14}O_2$		152	0.8	125	8.32 0.12	7360	λ= 1 17.9 mm +16° 11.5 mm +5°	-	-10
Di-isopropyl ether	$C_{10}H_{22}O$		108		158	11.0 0.0908	9640	λ= 1 10.5 mm λ= 1.5 6.75mm	-	-10
Di-allyl-glycol	$C_8H_{14}O_2$	※34.8	77	0.18	160		7860	λ= 1 14.5 mm +40° λ= 1.5 9.65 mm +25°	-	-10
Standard Gas Oil			45	2)	65-75				20 18	-20 -13

※Mixed O.N. with 75% I.G.7: O.N. 43.8

1) For explanation see text

2) Between n-hexane and tetrahydrofurane

Figure 5 - Starting Tests

Mixtures in volume %	ε	Ignition at °C
Butane peroxide in D 641 Ca4. 257	-	-10
Supraline 40% 2-Methylpentane 40% 3- " 20% n-Hexane NOZ 81.5 ROZ 83.5	-	-15
Petrol ether	-	-12
Di-ethyl ether + Methal pentane 50 + 50	- 12 11	-23 -16 -14
Di-ethyl ether + Acetone 75 + 25	19 16 14.5	-27 -25 -10
50 + 50	15 10.5 11	-22 -16 -10
25 + 75	16	-22
Di-ethyl ether + Normal gasoline 50 + 50	19 12.5 11.5 10.5	-26 -22 -14 -12
Di-ethyl ether + Ethyl alcohol 50 + 50	16 12 10.5	-24 -18 -10
Di-ethyl ether + Methyl alcohol 50 + 50	13	-17

Figure 6 - Starting tests with induction pipe injection.

Compression (ε) required at room temperature with 160 mm³/stroke of AS - material injected in the induction pipe.

Without gas oil; starting speed 100 rpm.

Test Series I

Ordinate: compression
Abscissa: Temperature

Figure 7 = Upper and lower compression limits.

Test Series II

Ordinate: compression
Abscissa: temperature

Figure 8 - (See page 10)

Figure 9 - Vapour pressure v. cetane number for starting tests with induction pipe injection.

Figure 8 - Starting tests with induction pipe injection (-20°)

Test Ser. II: Quantity of AS material injected in mm³/stroke with which ignition began. Compression ε = 16, without gas oil, AS material injection in the induction pipe.

Test Ser. III.: Compression ε with which ignition began. AS material : 160 mm³/stroke injected in the induction pipe, 30° after top centre (suction stroke). Gas Oil: 140 mm³/stroke injected in the combustion chamber 20° before top centre (compression stroke).