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Performance of Diesel Engines at High Altitudes

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ABSTRACT

Problems are encountered when conventional, normally aspirated diesel engines are operated at high altitudes. The results of a study carried out at the Indian Institute of Petroleum both on stationary and automotive diesel engines covering the principal problems of power loss and poor thermal efficiency are presented in this paper.

1. INTRODUCTION

In India, defence vehicles operate at high altitudes up to 6000 m. This is peculiar to our country as our international frontiers fall within the Himalayan ranges. The operating problems of engines at high altitudes are quite different as compared to those faced under mean sea level (msl) conditions. In case of vehicles, the altitude changes can be quite rapid, sometimes even during the same day. The major contributory factors for the operational problems are the rarefied atmospheric conditions and low temperatures prevailing at high altitudes. Diesel engines are used for most of the stationary and automotive applications. Some of the work related to operational problems of diesel engines at high altitudes, carried out at Indian Institute of Petroleum (IIP), is presented in this paper.

The major problem in high altitude operation is power loss due to reduction in air mass flow and poor combustion efficiency due to change in the resulting injection characteristics. Other attendant problems are poor thermal efficiency, higher smoke density and exhaust temperatures depending upon the altitude as compared to msl conditions.

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2. POWER LOSS IN ENGINES

The power output of diesel engines falls at the rate of about 1 per cent for every 100 m altitude. Some solutions to recover the power loss, such as supercharging, increasing rotational speed and using higher horse power units in place of the existing ones were suggested by some investigators[1]. Most of these methods are based, on the principle of increasing the breathing capacity of the engine and were not ultimately favoured due to various practical difficulties such as non-availability of suitable equipment to match the existing engines and in some cases involvement in major design problems.

2.1 Studies on Compensating Power Loss

A different approach to solve the problem of power loss in diesel engines was tried at IIP. This approach aimed at increasing the air utilisation factor by increasing the charge homogeneity by inducting volatile fuels through carburation. The quantity of diesel fuel injected was reduced in proportion to the quantity of fuel carburetted. Investigations[2] showed that charge homogeneity increased with increase in the quantity of fuel carburetted, though this quantity was limited by the anti-knock quality of the fuel and the inherent air utilisation of the engine which depends upon the combustion chamber design.

Under simulated high altitude conditions in the laboratory corresponding up to 3350 m altitude, experiments were carried out on six different types of diesel engines. To simulate high altitude conditions, intake air was throttled and passed to the engine through a surge chamber. The supplementary fuel chosen was aviation gasoline 115/145 due to its knock-free inductability. This was introduced through a simple carburettor with a variable jet. The details of the engines and the results are given in Table 1.

To study the deleterious effects of inducting gasoline, if any, an endurance test of 500 hours duration was carried out on engine B. The engine performance was found to be normal during the entire test and there was no malfunctioning of any component. After stripping, examination of engine components for wear and deposits also did not indicate any ill-effect due to carburation.

These studies showed that it is possible to recover to some extent the power loss of engines by increasing the homogeneity of the charge. There has been a marked improvement in the specific fuel consumption, smoke density and other performance parameters. In pre-chamber engines, where the air utilisation is quite high, the inductable quantity of supplementary fuel and the power gain were not significant. As the normally aspirated automotive engine widely used in the forward areas, was of the pre-chamber type and as the frequent changes of speed, load and altitude called for sophisticated governing system, further work on automotive engines was not carried out. However, for quiescent chamber engines having low air utilisation factor, the gains were quite significant. Such engines are used in the forward areas for stationary applications and further work was carried out on one such typical engine.

Table 1. Details of engines and results

Sl. No	Parameter	A	B	C	D	E	F
1.	No. of cylinders		3	2	6	6	6
2.	Displacement (litres)	0.553	4.27	1.318	5.751	5.00	4.58
3.	Compression ratio	16:1	16.5:1	16.5:1	16:1	17.4:1	19.5:1
4.	Combustion chamber type	quiescent	quiescent	quiescent	quiescent	pre-combustion	pre-combustion
5.	Manufacturers' rating (bhp @ rpm)	5 @ 1500	15 kVA 1000	12.5 @ 1500 (alternator rating 6 kW at 1500 rpm)	69 @ 1650	80 @ 2200 (compressor rating 6.7 kg/cm^2 receiver pr @ 1750 rpm)	110 @ 3000
6.	Smoke-limited output (bhp @ rpm)	5 @ 1500	17.00 @ 1000	6.25 kW @ 1500 rpm (alternator)	48.00 @ 1600	64.00 @ 1750 rpm	84.00 @ 2800
7.	Output at 20 cm Hg depression (bhp @ rpm)	3.5 @ 1500	13.00 @ 1000	alternator output 3.5 kW @ 1500 rpm	31.00 @ 1600	compressor output 3.5 kg/cm^2 receiver pr @ 1750 rpm	
8.	Output after carburation (bhp @ rpm)	5 @ 1500	17.00 @ 1000	6.00 kW @ 1500 rpm (alternator)	40.00 @ 1400	4.8 kg/cm^2 receiver pr 1750 rpm (compressor)	
9.	Supplementary fuel inducted (%)	67	40	78	45	40	

2.2 Studies in Altitude Chamber

These studies were carried out on a 2-cylinder air-cooled diesel engine coupled to an alternator (engine C). Fig. 1 gives the general performance of the engine and Fig. 2, the performance under reduced pressure conditions. The smoke-limited output (at 8 on Bacharach scale) came down from 6.25 to 3.5 kW at 20 cm Hg depression. With carburation the output could be maintained at 6.0 kW (the rated output) up to 20 cm Hg depression.

As these experiments were quite promising, it was considered desirable to develop a suitable regulator to (a) prevent the induction of supplementary fuel when the engine could be operated with diesel fuel alone up to the smoke-limited power, (b) vary the point of induction depending on altitude, and (c) vary the quantity of supplementary fuel inducted depending on load. The laboratory experiments were carried out in an altitude chamber (Fig. 3) and the regulator developed is shown in Fig. 4.

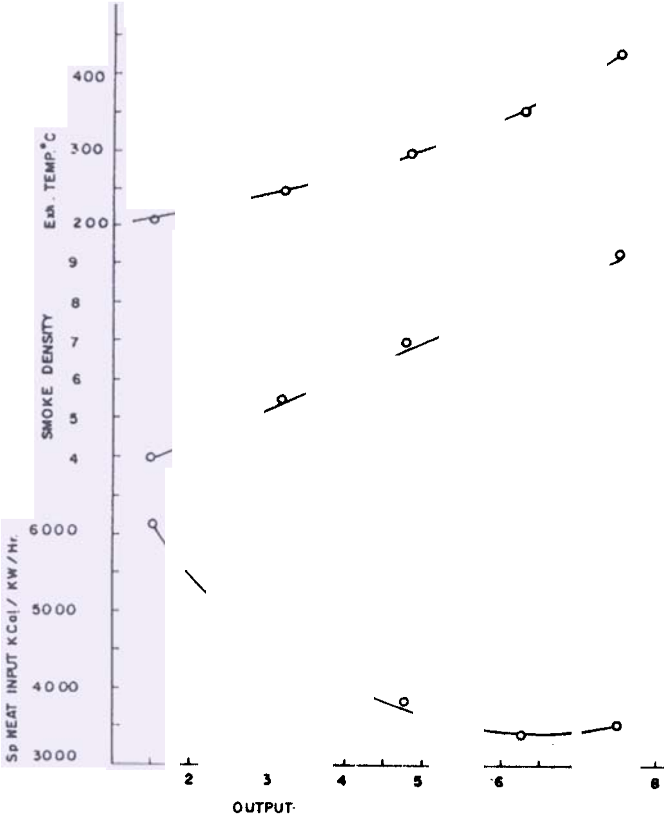

Figure 1. General performance of engine C coupled to an alternator.

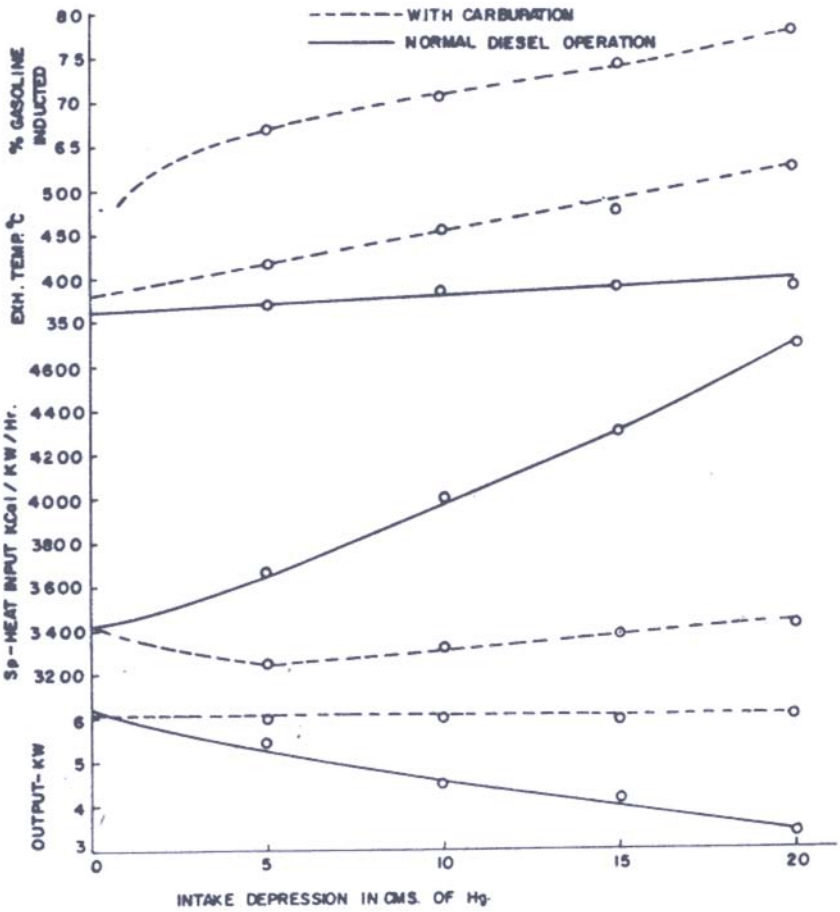

Figure 2. Performance of engine C (smoke-8) under reduced pressure conditions.

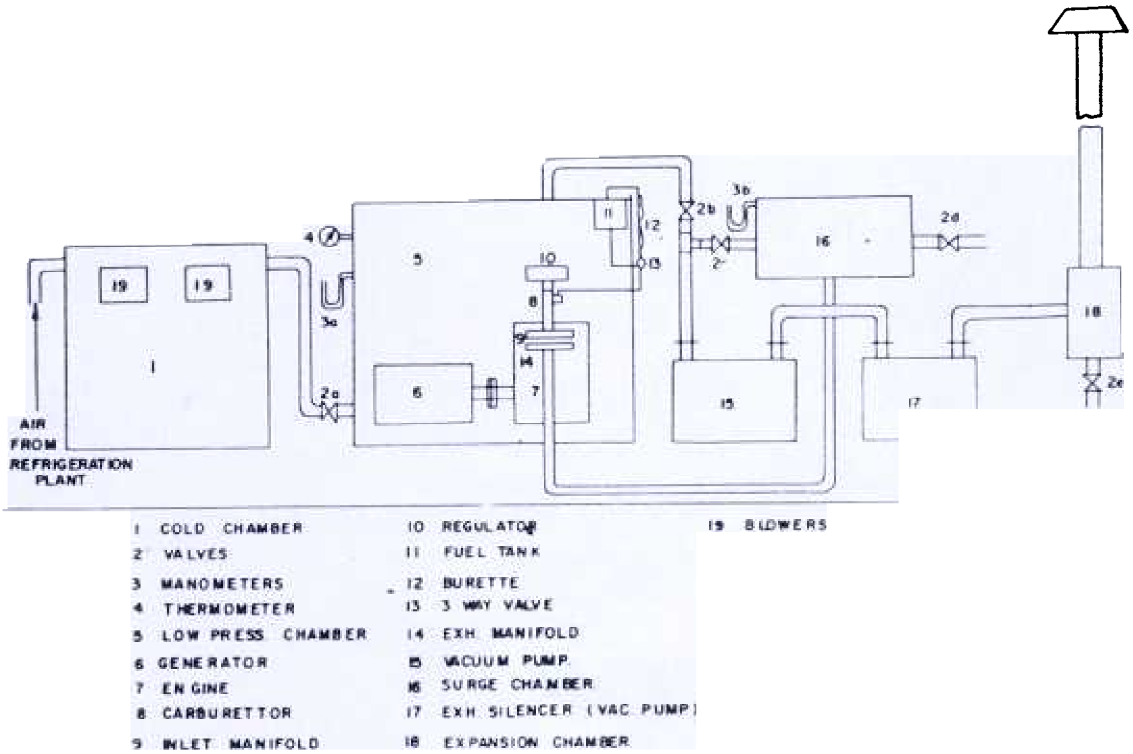

Figure 3. Schematic diagram of altitude chamber.

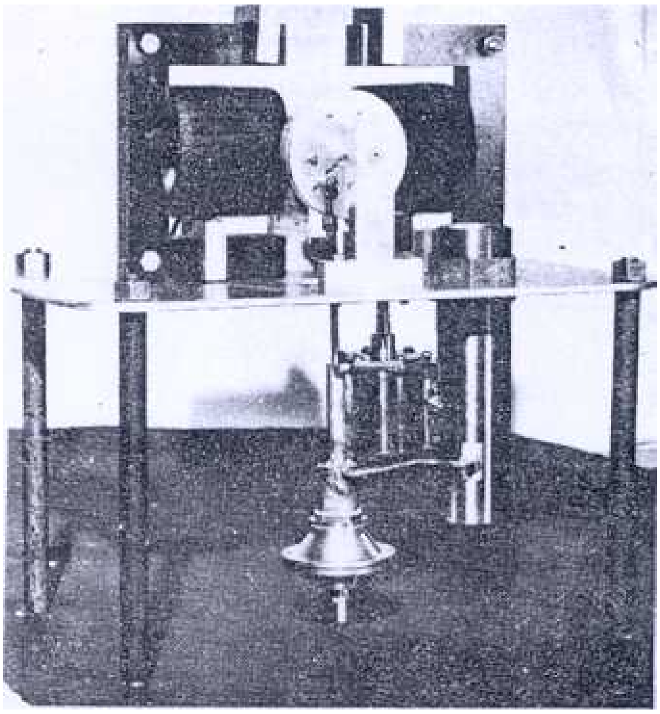

Figure 4. Regulator for bi-fuel operation of engine C

2.2.1 Field Trials

With the cooperation of Research and Development Establishment (Engineers), Pune, field trials with the same engine unit with regulator were carried out at 3230 and 4020 m altitudes in the forward areas and the results are presented in Figs. 5 and 6. At 3230 m altitude, the smoke limited power output of 4.42 kW at a speed of 1510 rpm obtainable with diesel fuel alone could be increased to 6.1 kW at a speed of 1535 rpm with induction of supplementary fuel, indicating a gain of 28 per cent. On volume basis, the percentage of supplementary fuel inducted was 38.5 per cent of the total. Other parameters also indicated an improvement in the performance of the engine. Similarly at 4020 m altitude the smoke-limited power of 3.72 kW with diesel fuel only could be increased to 5.28 kW at a speed of 1540 rpm, a gain of 26 per cent of the rated output with 38 per cent of the supplementary fuel.

These experiments confirmed that it is possible to recover the power loss of stationary quiescent chamber engines to certain extent depending on altitude and develop suitable regulator for bi-fuel operation of the engines.

3. PERFORMANCE IMPROVEMENT

3.1 Studies by Changing Injection Pressure and Timing

The rate of deterioration of diesel engine performance with increase in altitude is accelerated due to drop in combustion efficiency caused by increase in the ignition delay. The decrease in power output therefore is greater than that can be accounted for, by the reduction in air-mass flow at high altitude. The injection pressure and timing set for optimum performance at msl conditions will not be ideal under changed operating conditions. At high altitudes, besides increased delay, lower charge density permits greater penetration of the fuel jet. A greater part of the fuel that impinges on the cylinder wall may not effectively take part in the combustion process at all. This contributes to poor efficiency, higher exhaust temperatures and smoke density.

Under simulated altitude conditions a multi-cylinder diesel engine coupled to a dynamometer (engine F) was used for the studies[3]. The performance of the engine at ambient conditions with standard settings and up to 15 cm Hg depression corresponding to 2600 m altitude with different injection pressures were studied. The results are presented in Figs. 7 and 8. Studies were also carried out by varying the injection timing. In this particular case no significant improvement in performance was observed.

By reduction in the injection pressures, the engine performance improves with respect to specific fuel consumption and power output. Under simulated conditions corresponding to 2600 m altitude, reducing the injection pressure from 1900 to 1500 psi results in a power gain of up to 7.66 per cent in the speed range of 1000 to 2000 rpm. Similarly saving in specific fuel consumption at 1700 psi injection pressure varies

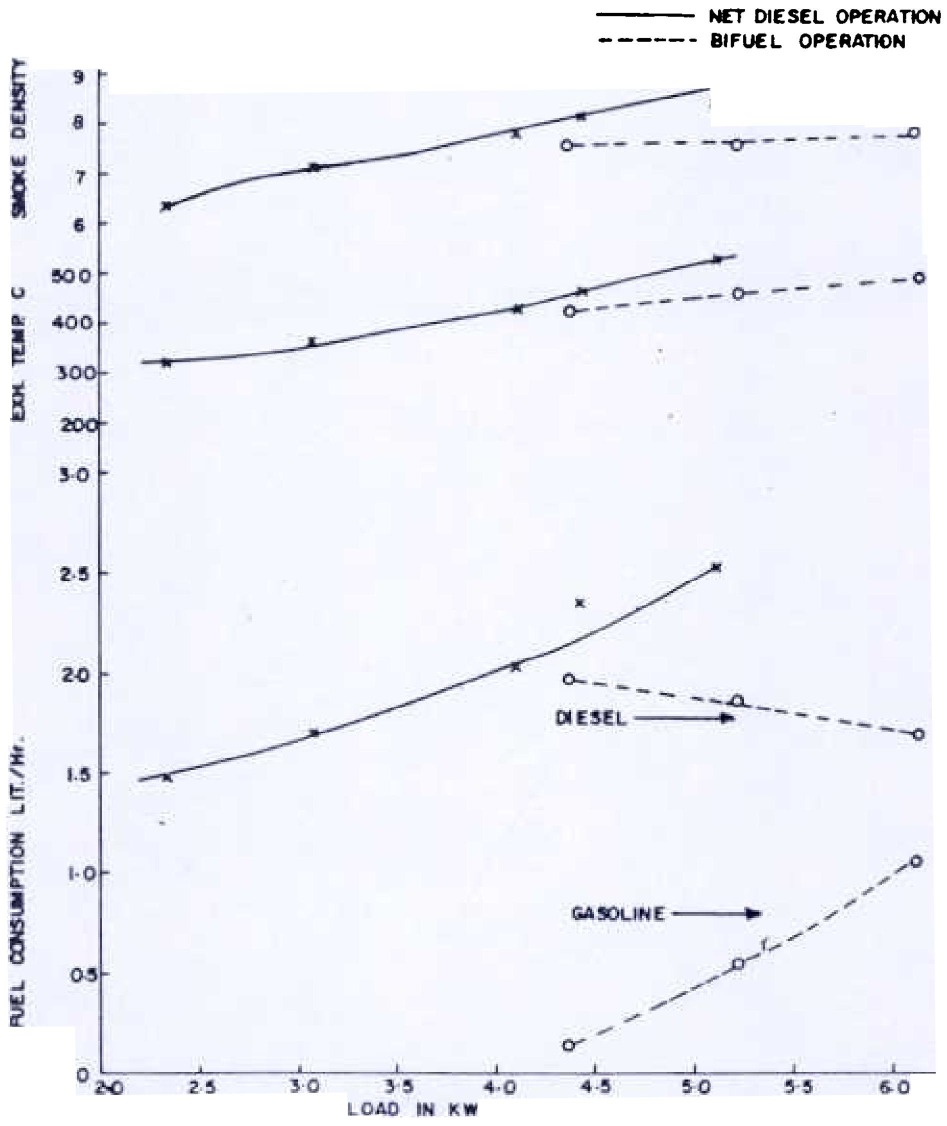

Figure 5. Performance of engine C at 3230 m (10,600 ft) altitude

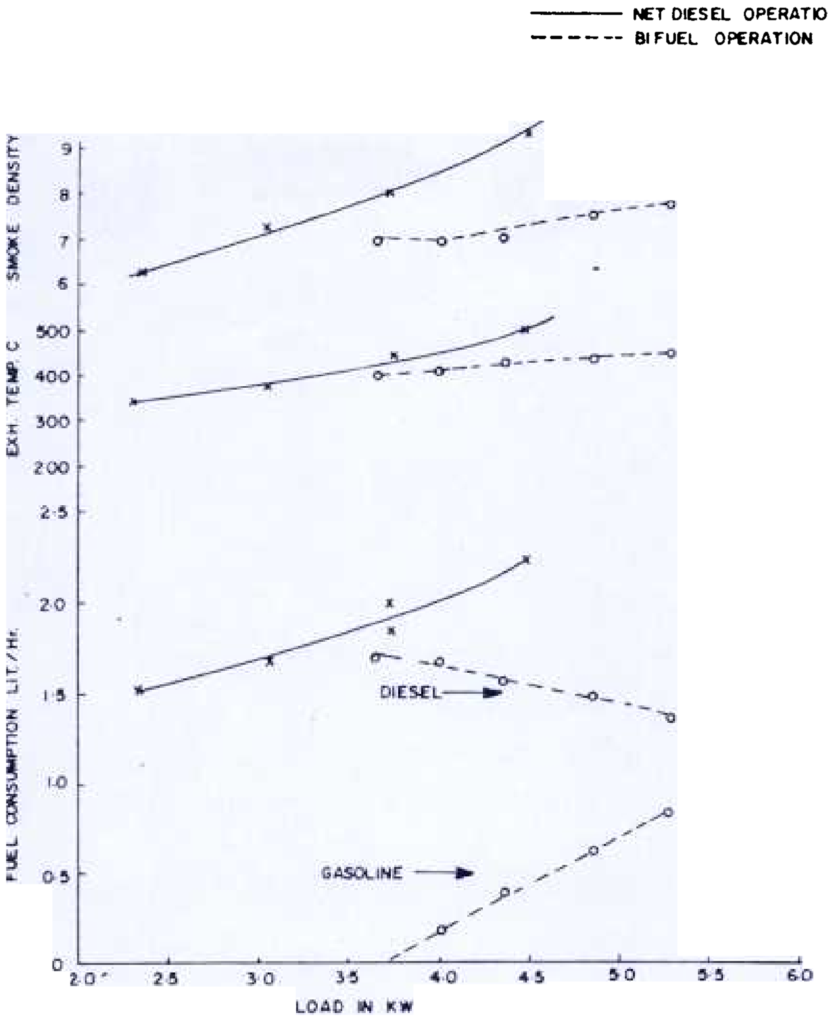

Figure 6. Performance of engine C at 4020 m (13,200 ft) altitude

from –2.4 to +7.7 per cent and at 1500 psi injection pressure, it varies from –1.4 to +6.25 per cent. Further experiments at higher depressions and lower injection pressures could not be carried out due to difficulties in operating the engine under simulated conditions.

3.2 Studies by Limiting Fuel Input

Engines are rated to give optimum performance at msl conditions. Above msl conditions, due to reduction in air-mass flow, the engine would be unable to utilise fully, the fuel supplied by the pump at full load conditions. This can lead to poor thermal efficiency, higher exhaust temperatures, higher smoke density, reduction of oil drain and overhaul periods resulting in high operational costs and reduction of engine life.

These problems were faced by the army in case of normally aspirated automotive diesel engines used in the forward areas.

The solution to these problems was to limit the maximum fuel input depending on altitude (air availability). In the case of automotive engines operating under varying altitudes, manually limiting the maximum fuel delivery of the pump was neither advisable nor practical. So studies[4] were taken up at IIP to develop a device to limit the maximum fuel delivery depending on the altitude for optimum performance of the engine.

3.2.1 Laboratory Studies

The performance of the engine (engine F) was studied under ambient conditions and it was observed that the maximum torque and minimum specific fuel consumption (sfc) were recorded at a speed of 1600 rpm. Again the performance study was carried out at constant speed (1600 rpm) with the original setting of the pump and manually limiting the maximum fuel delivery for ensuring optimum air-fuel ratio of the engine at different depressions up to 20 cm Hg corresponding to 3350 m altitude. The results are presented in Fig. 9.

By limiting the fuel delivery, the objective was to reduce the later part of the injected fuel which may not effectively take part in the combustion process due to unfavourable conditions. With the result, for almost the same power output there is

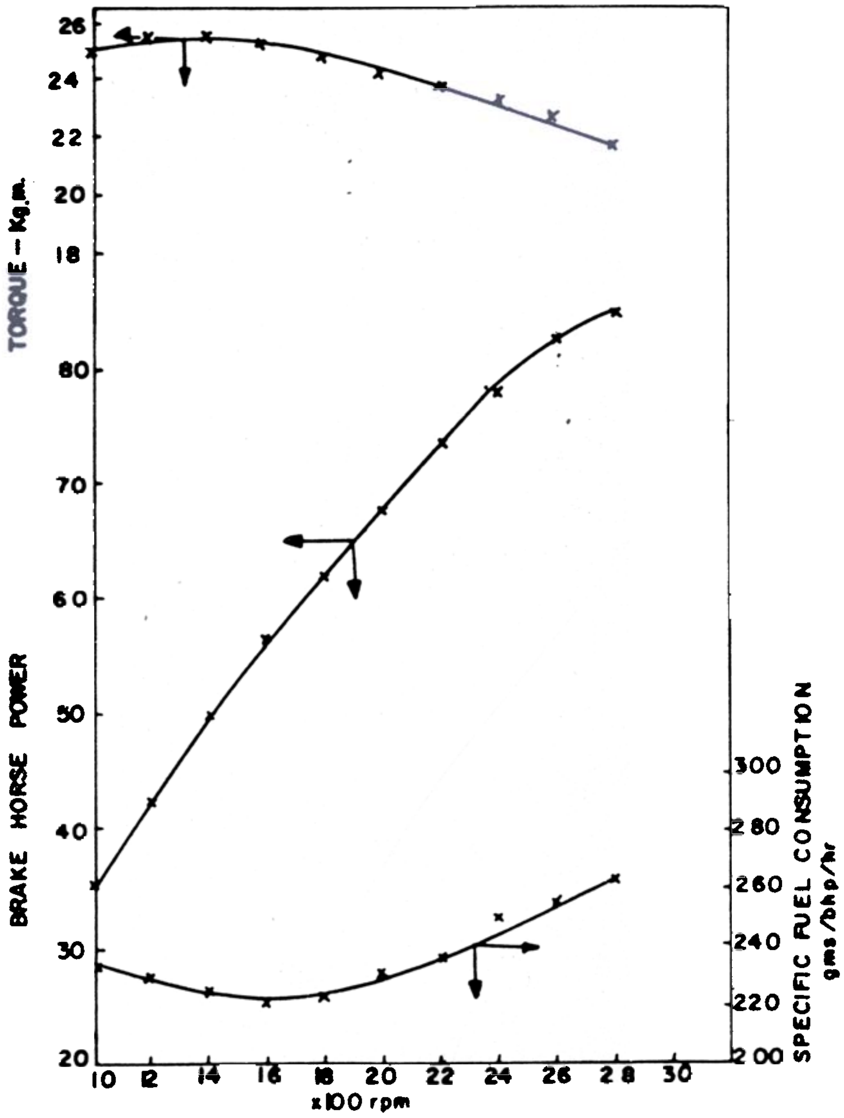

Figure 7. Performance of an automotive diesel engine at ambient conditions.

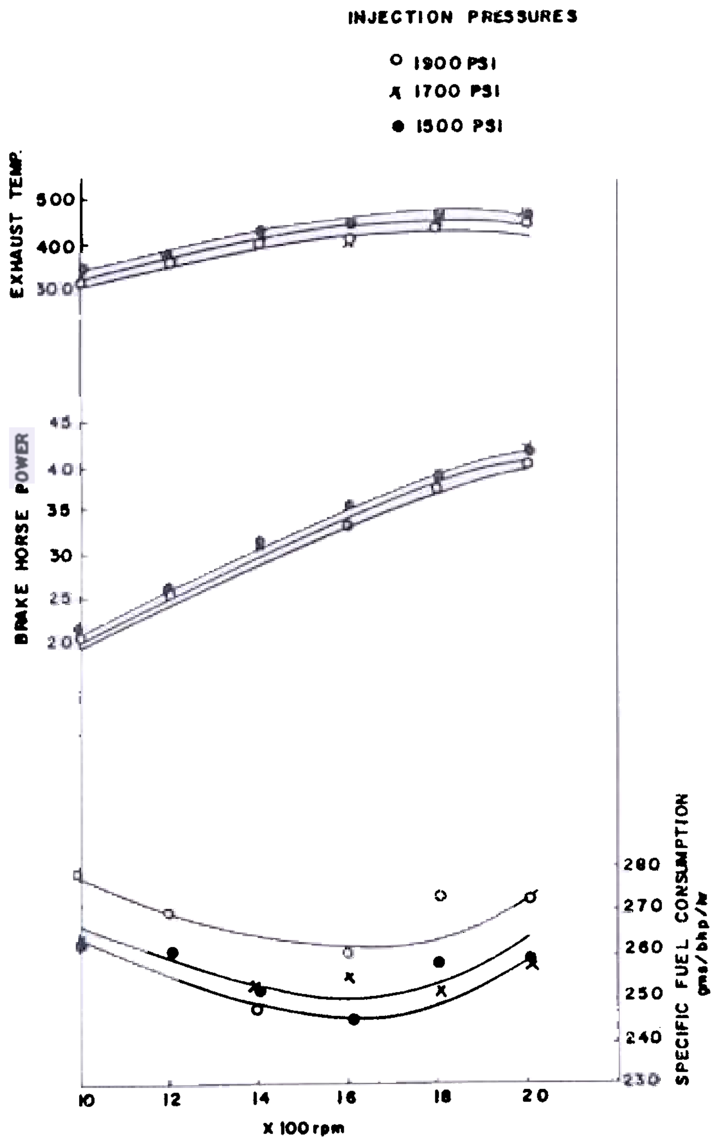

Figure 8. Performance at simulated altitude conditions corresponding to 2600 m, varying the injection pressures.

a gradual improvement in thermal efficiency with increasing depressions and at 20 cm Hg depression gain in bsfc is almost 24 per cent. Consequently the smoke densities and exhaust temperatures are also lower.

To maintain the same fuel-air ratios, a device was developed (Fig. 10). It consists of a pressure sensing element which carries a tapered needle Depending on the altitude, the projection of the needle varies and limits the travel of the fuel pump control rod operating lever, thereby controlling the maximum fuel delivery. For starting the engine, usually more than the full load quantity of the fuel is required. Keeping this in view, provision to disengage the needle was also incorporated. This device was calibrated by carrying out trial runs on the test-bench.

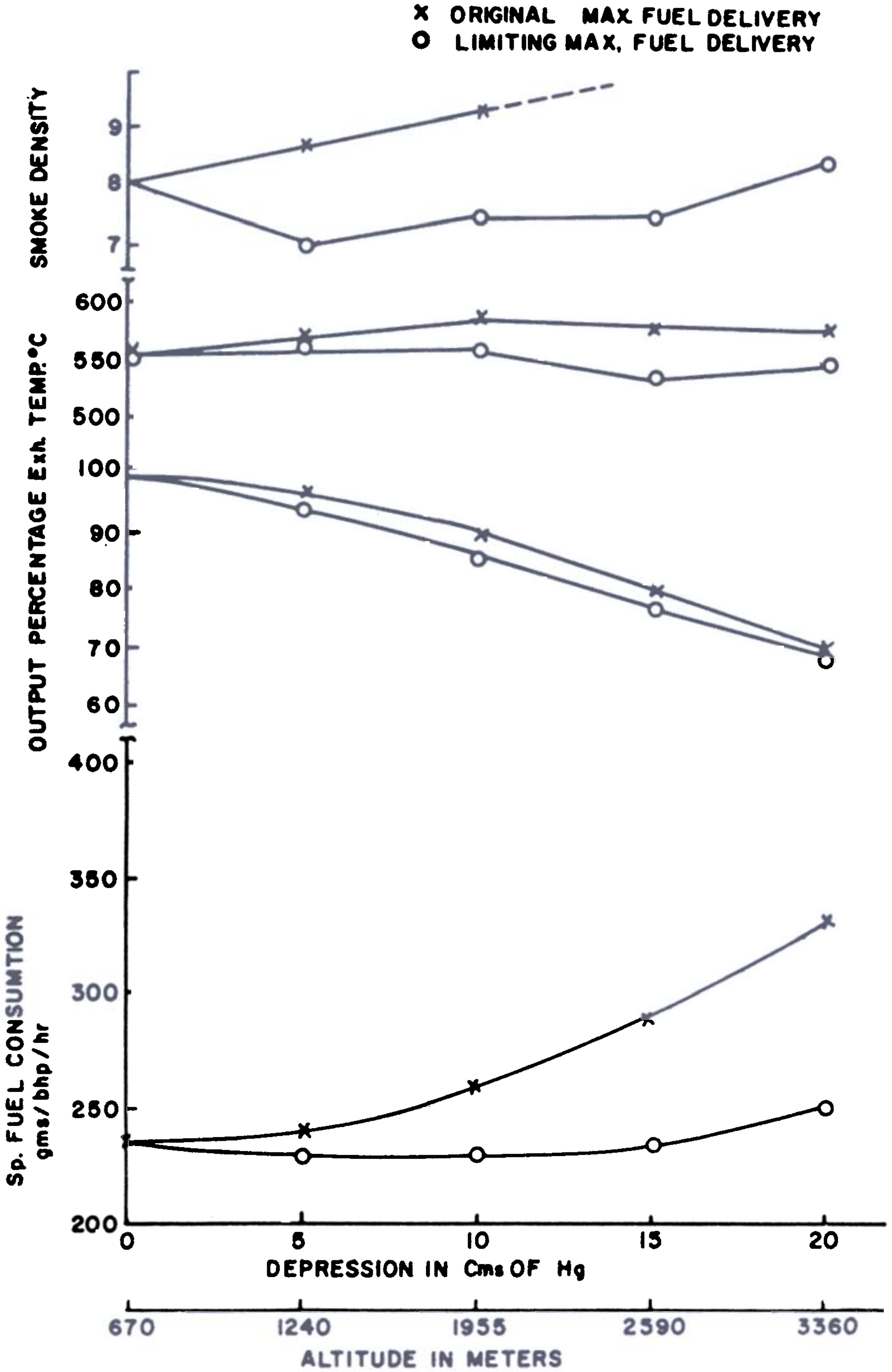

Figure 9. Performance of automotive diesel engine F under simulated altitude conditions (at 1600 rpm).

3.2.2 Field Trials

With the cooperation of Vehicles Research and Development Establishment, Ahmednagar, a vehicle was fully instrumented and trials were carried out at Mussoorie and then at 3350 m altitude in forward areas. The results are presented in Table 2. With the device under full load conditions (maximum fuel delivery), decrease in fuel

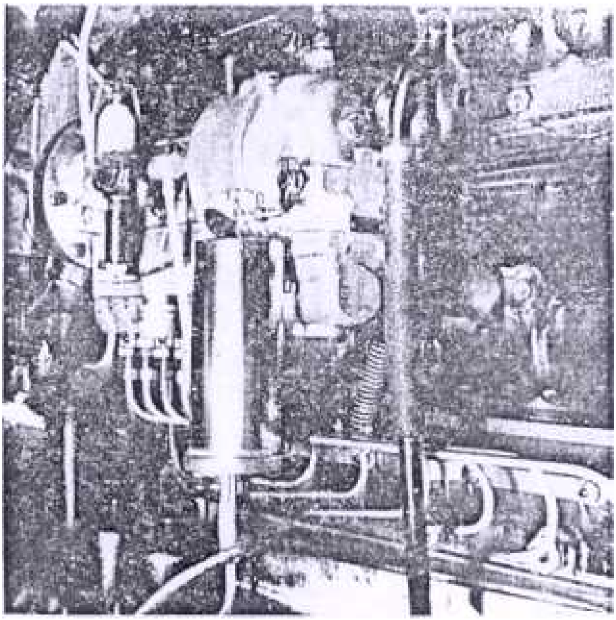

Figure 10. Photograph of the device for limiting maximum fuel delivery of engine F.

Table 2. Field trial results

	Without device	With device
Under full load maximul fuel delivery conditions		
Engine speed (rpm)	2650	2650
Vehicle speed in 3rd gear (kmph)	20 (av.	20 (av.)
Fuel flow (secs for 100 cc)	14.23	17.00
Exhaust temperature (°C)	625	600
Smoke density (5 secs)	Black	8+
Under average operating conditions		
Average fuel consumption for 30 km (litres)	13.2	12.2
Vehicle performance acceleration (secs)		
0–30 kmph	40.00	39.50
0–40 kmph	56.00	55.00
15–30 kmph	49.81	50.66
Maximum speed attained (kmph)	40	40
Gradeability in second gear	20–25%	

consumption was approximately 16 per cent. This was because, it was observed, that with the laboratory setting, acceleration characteristics of the vehicle were affected and minor adjustments were made in the settings to increase fuel delivery. The exhaust temperature and smoke density were also relatively lower under average operating conditions. Decrease in fuel consumption was found to be $7\frac{1}{2}$ per cent. With the device in operation tests for acceleration and gradeability were also found to be satisfactory.

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