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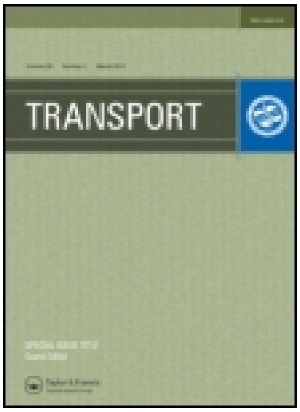

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Effects of altitude on the soot emission and fuel consumption of a light-duty diesel engine

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EFFECTS OF ALTITUDE ON THE SOOT EMISSION AND FUEL CONSUMPTION OF A LIGHT-DUTY DIESEL ENGINE

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Abstract. A four-cylinder, direct-injection (DI) diesel engine was used to study the effects of altitude on the variations of the exhaust soot emission and engine performance. The experiments were conducted in Mashhad, Iran, at an altitude of 975 m above sea level. A three-lobe rotary blower of Roots type was employed in order to simulate the altitudes down to 350 m by increasing the inlet manifold pressure of the engine. The tests were performed based on the ECE-R49 test cycle, and for each testing point, the experiments were repeated for five boosting pressures which correspond to five different altitudes. Results indicate that with increasing the altitude from 350 m to 975 m, the soot emission increases about 40%. This increase is due to the relatively lower the air density introduced into the cylinders in higher altitudes that leads to the increase of autoignition delay time which could shorten the late combustion phase; hence, the soot burnout process deteriorates. Also it was found that at low engine loads, the Brake-Specific Fuel Consumption (BSFC) increases about 20% with raising the altitude from 350 m to 975 m. At higher loads, the raising rate of fuel consumption is insignificant. The effects of altitude on the other engine parameters such as induced air mass flow rate, volumetric efficiency, equivalence ratio, and exhaust temperature were investigated as well. In addition, a sensitivity analysis was conducted and the results revealed that among the engine parameters, the soot emission alteration has the most sensitivity to the change of the altitude.

Keywords: altitude; diesel engine; soot emission; brake-specific fuel consumption; boosting pressure.

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Introduction

The enormous magnitude of emissions produced by automotive engines consist the major portion of the environmental pollutions (Abdel-Rahman 1998). Diesel engines among the internal combustion engines have drawn a great attention due to their various applications in transportation industries or stationary power-generation units because of their high torque output, size flexibility, durability, and fuel efficiency (Ghazikhani *et al*. 2010). In the last decades, reduction of soot and NO_x emissions from diesel engines was extensively pursued by the researchers and also new stricter emission control policies like EURO-V highlight the importance of NO_x and soot emission reduction because of their hazardous effects on human health and the environment (Zannis *et al*. 2007).

Apart from being toxic, nitrogen oxides are important ingredients in the photochemical smog reactions. Also the health problems associated with inhaled Particulate Matter (PM) are cancer, mutations, cardiopulmonary ailments, and lung damage (Kitsopanidis 2004). Besides, the effects of pollution emissions from diesel engines on the environment include visibility reduction, water and soil pollution, global climate change, etc. (Lloyd, Cackette 2001). In addition to human health and the environment problems, it should be also noted that the emissions may have injurious consequences on the maintenance and lifetime of diesel engine. For instance, the contamination of lubricating oil by diesel soot is an important factor leading to the increased engine wear (George *et al*. 2007).

Soot formation is a result of incomplete combustion, which is a sign of nonoptimal efficiency of the combustion process (Bladh *et al*. 2006). Soot is formed in the diffusion flames, just after the lift-off rich premixed burn region, its size and mass increase when traveling inside the diffusion flame, and finally, it is somewhat oxidized in the diffusion flame front. Therefore, final soot emissions depend on the amount of both formed and oxidized soot (Arrègle *et al*. 2008).

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There are extensive researches on the effective parameters on the PMs and diesel soot emission. PMs include various solid compositions suspended in combustion products. The great portion of PM encompasses soot mainly as a result of fuel pyrolysis. According to the available studies, the in-cylinder parameters such as fuel injection pressure, injection timing, spray geometry, air/fuel swirl ratio, turbo-charging, combustion chamber shape, wall temperatures, and Exhaust Gas Recirculation (EGR) seem to play a critical role in terms of controlling the diesel combustion emissions. The effect of engine altitude on the engine performance and emissions can be simulated by the variations of the intake and exhaust manifold pressure. However, there are other environmental factors rather than air pressure that can be taken into consideration for perfect altitude simulation such as average temperature and air humidity. Human *et al*. (1990) and Chaffin and Ullman (1994) simulated the changes in altitude by reducing the pressure in both the intake and the exhaust route of a diesel engine. Their results revealed that emissions of PM, HC, CO, CO_2, and smoke generally increases with increasing altitude. Also, they found that the changes of NO_x emissions with increasing altitude are insignificant. Lizhong *et al*. (1995), using a similar method, obtained similar results. Based on the measurements made at 1609 m and sea level on three engines, Graboski and McCormick (1996) reported that CO and particular matter emissions increased with increasing altitude but again no considerable change in NO_x emissions was observed. Bishop *et al*. (2001) investigated the altitude alteration on the exhaust emissions of on-road 5772 heavy-duty diesel trucks at five locations in the USA and Europe by remote sensing measurements. Their research showed the emissions such as carbon monoxide, hydrocarbons, and nitric oxides slightly increase with increasing altitude. Benjumea *et al*. (2009) studied the effect of altitude on the performance and combustion characteristics of a HSDI diesel engine under steady-state operating conditions. Their work indicated that the fuel consumption increased when elevating from 500 to 2400 m. However, they did not study the effect of altitude on exhaust emissions of the engine.

In order to compensate the negative effects of increasing altitude on the engine performance and emissions, some investigations are made which concerned the alternative fuels impact and their contributions to the combustion characteristics at high altitudes. Perez and Boehman (2010) studied the effects of oxygen enrichment of intake air on the engine performance at simulated high-altitude conditions. It was revealed that power output depends greatly on the engine load and was not improved by the use of oxygen-enriched air, but it did not decrease significantly for altitudes up to 2600 m. They also declared that the peak combustion temperatures were significantly affected by simulated altitude and oxygen volume fraction, but the effect of simulated altitude was of larger magnitude than the effect of oxygen volume fraction. Also, Lei *et al*. (2011) examined different ratios of ethanol–diesel blends on emissions and performance of a turbo-charged diesel engine running at different atmospheric pressures. The results indicated the improvement of the engine BSFC while operating with ethanol–diesel blends under different atmospheric pressures. The changes of HC and CO emissions with engine torque and speed strictly depend on the altitude and are not following a specific trend. Smoke emissions decrease obviously with the increasing percentage of ethanol in blends, especially atmospheric pressure below 90 kPa.

Benjumea *et al*. (2009) studied the effect of utilizing palm oil biodiesel on a turbo-charged diesel engine operating at different altitudes above sea level. The remarkable conclusion they came up with was that biodiesel fuelling and altitude had an additive effect on the advance in injection and combustion timings. The duration of the premixed combustion stage increased with altitude and decreased with biodiesel.

In the following study, the effect of altitude on the exhaust soot emission, BSFC and other engine parameters of a light-duty DI-diesel engine were experimentally investigated. The altitudes are selected in the range below 1000 m from sea level which has rarely been studied in the literature before. The tests were performed according to the ECE-R49, 13 mode standard tests. The reduction of altitude from the test location was simulated by increasing the inlet manifold pressure using a Roots blower. Finally, a sensitivity analysis is conducted to specify the most-affected engine parameter by change of altitude.

1. Experiments

The experimental set-up for the tests is shown in Figure 1. The test engine is a four-cylinder DI-diesel engine with main specifications as given in Table 1. The experiments were conducted in the IC Engines laboratory, in the School of Engineering of the Ferdowsi University of Mashhad at an altitude of 975 m above sea level. ECE-R49 test cycle is followed to assess the engine performance and the black smoke emission. This standard is a 13-step test in which the engine is studied under several operating conditions. This test cycle assigns a weighting factor to each test step which implies the predominance of the conditions under which the engine is running. According to ECE-R49 test cycle, the engine operation is examined under idle and two other engine speeds, i.e. speed of part load and full load. In each engine speed, five different loads are applied to the engine crank shaft in an increasing or decreasing manner. The principle testing points are displayed in Table 2. The reduction in altitude to 350 m above sea level, which corresponds

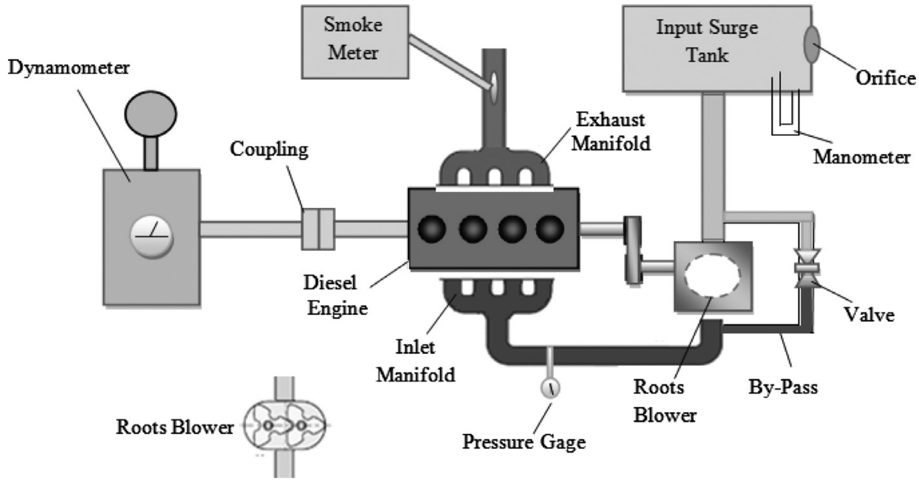

Fig. 1. Experimental layout for tests on the diesel engine

to the increase of apparent barometric pressure, was simulated with increasing the inlet manifold pressure of the engine by using a three-lobe rotary blower of the Roots type. The performance map of Roots compressor has already been available. According to a given speed and pressure ratio, the input power of compressor can be found by the performance map. Once the operator changes the boosting pressure of the inlet manifold, without changing the position of engine fuel pump rack, the external load applied by dynamometer is changed to maintain the engine speed on a constant level which is dictated by ECE-R49 standard. It should be stated that the overall output load of the engine is a summation of the load consumed by the compressor and the load applied by the dynamometer. The ECE-R49 standard test was repeated for five boosting pressure levels including 10, 20, 30, 40, and 50 mmHg separately, where each 10 mmHg approximately corresponds to a decrease of 125 m in the altitude (Portland State Aerospace Society 2004). Therefore, the results of experiments can be related to the engine performance in six different locations with the altitudes of 975, 850, 725, 600, 475, and 350 m above sea level. Some sets of experimental data are presented in Table 3. The variations of the exhaust back-pressure with altitude could be neglected due to the high in-cylinder blow-down pressure which makes the pressure difference between environment and the cylinder inconsiderable (Heywood 1988).

Variations of air temperature against altitude are not normally predictable in the low-altitude regions. However, the dependence of temperature and altitude

Table 1. OM-314 engine specifications

Engine and supercharger specification	
Engine type	Four-stroke diesel engine
Number of cylinders	Four
Combustion chamber	Direct injection
Piston geometry	Bowl-in shaped
Bore × stroke (mm)	97 × 128
Piston displacement (cc)	3784
Compression ratio	17:1
Maximum power (hp)	85
Maximum torque (N·m)	235
Maximum speed (rpm)	2800
Supercharger type	Roots compressor (three-lobe rotary blower)

Table 2. ECE-R49 13 points test operating conditions

Mode No.	Torque (N·m)	Speed (rpm)	Load (%)	W_f
1	3	950	–	0.083
2	23	1750	10	0.08
3	59	1750	25	0.08
4	117	1750	50	0.08
5	176	1750	75	0.08
6	230	1750	100	0.25
7	3	950	–	0.083
8	210	2400	100	0.1
9	157	2400	75	0.02
10	105	2400	50	0.02
11	52	2400	25	0.02
12	21	2400	10	0.02
13	3	950	–	0.083

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Table 3. A set of processed data

Altitude (m)	Mode No.	*BP* (mm Hg)	S_{soot} (g/kW·h)	*BSFC* (g/kW·h)	$\dot{m}_a$ (kg/h)	Vol. efficiency (%)	$T_{exhaust}$ (K)
350	2	50	0.10932	500.537	211.14	92.91	461
	4	50	0.20672	238.732	209.988	92.95	615
	6	50	1.45159	218.887	200.844	93.25	754
	8	50	1.05679	214.759	249.3	83.04	863
	10	50	0.68632	260.503	250.488	82.87	726
	12	50	0.19845	486.287	252.72	82.82	606
475	2	40	0.11071	514.306	208.188	92.74	461
	4	40	0.21350	239.364	207.036	92.77	615
	6	40	1.50548	208.754	205.236	92.85	761
	8	40	1.04361	203.277	245.412	82.42	864
	10	40	0.60381	256.688	246.6	82.44	721
	12	40	0.20104	501.619	248.328	82.42	599
600	2	30	0.11227	531.592	203.364	91.71	461
	4	30	0.20497	244.628	242.82	91.74	620
	6	30	1.66503	224.636	199.476	92.36	765
	8	30	1.14333	212.884	239.4	81.59	865
	10	30	0.58349	260.426	240.768	81.50	722
	12	30	0.15502	531.188	202.248	81.47	599
725	2	20	0.11450	558.405	199.26	91.51	463
	4	20	0.20394	244.682	200.7	91.54	622
	6	20	1.81509	225.622	197.352	91.62	788
	8	20	1.17095	214.129	234.036	81.06	873
	10	20	0.52243	262.841	236.736	81.04	722
	12	20	0.15721	548.699	239.292	80.99	600
850	2	10	0.11523	564.274	177.3	91.30	464
	4	10	0.19834	238.047	175.932	91.32	617
	6	10	2.21883	218.267	172.836	91.42	783
	8	10	1.25765	219.025	224.424	81.32	868
	10	10	0.49692	259.083	226.368	81.09	719
	12	10	0.16104	566.513	227.052	81.03	600
975	2	0	0.09635	578.670	177.3	84.04	473
	4	0	0.11923	234.020	175.932	84.12	633
	6	0	2.35952	212.062	172.836	84.43	834
	8	0	1.27613	228.812	224.424	79.72	903
	10	0	0.55750	274.717	226.368	79.93	718
	12	0	0.22699	585.595	227.052	79.96	603

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should be considered in the aviation science. In the current study, the inlet and exhaust manifold temperatures were monitored using K-type thermocouples, while the inlet and exhaust manifold static pressures were measured using Bourdon pressure gauge. It should be noted that the air dynamic pressure is directly proportional to the piston speed (gas velocity) which does not change with altitude in the same test mode. So in a particular test mode, the amount of inlet mass flow is dependent on the static pressure which changes with altitude. Therefore, we only need to measure the static pressure.

External torque was exerted to the engine by a Froude hydraulic dynamometer, and the engine speed was recorded using a magnetoelectrical speed sensor. The soot emission was recorded by means of an AVL-415 smoke meter which could also measure the exhaust opacity by Flow Soot Number (FSN). In its system, after the filter paper is being exposed to the exhaust flow sample, the bulb illuminates the filter paper via a light guide. The reflected light, which depends on paper blackness, is registered by means of a photodiode. The measurements accuracies of the devices are listed in Table 4.

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2. Notations

A_0 – orifice area (m^2);
C_d – discharge coefficient;
C_f – power correction factor;
$\dot{m}_a$ – air mass flow rate (kg/s);
$\dot{m}_f$ – fuel mass flow rate (kg/s);
$\dot{m}_{soot}$ – soot mass flow rate (g/h);
N – engine speed (rpm);
$P_{b,s}$ – corrected brake power (kW);
P_m – measured ambient-air absolute pressure (kPa);
$P_{m,y}$ – measured ambient-water vapor partial pressure (kPa);
$P_{s,d}$ – standard dry-air absolute pressure (kPa);
P_e – exhaust pressure (kPa);
P_i – inlet manifold pressure (kPa);
$\dot{Q}_e$ – volumetric flow rate of exhaust gas (m^3/s);
S_{soot} – specific soot emission (g/kW·h);
T – engine torque (N·m);
T_e – exhaust temperature (C);
T_m – measured ambient-air temperature (K);
T_s – standard ambient-air temperature (K);
t_f – required time for consumption of 50 cc of fuel (s);
w_f – weighting factor;
$\Delta h_{orifice}$ – difference in elevation of orifice (m);
ρ_{soot} – exhaust soot density (mg/m^3);
ρ_{air} – air density at the intake manifold (kg/m^3);
ρ_e – exhaust gas density (kg/m^3);
ρ_l – manometer liquid density (kg/m^3);
ρ_f – fuel density (kg/m^3);
η_v – volumetric efficiency of the cylinder;
V_d – displacement volume of the cylinder (m^3).

Table 4. Accuracies of the measurement

Measurement	Accuracy
Pressure	±1 mm Hg
Soot	±1 mg/m^3
Speed	±1 rpm
Temperature	±0.1 ºC
Torque	±0.5 N·m

3. Brake-specific soot calculation

ECE-R49 test consists of the multimode steady-state tests, and each mode has a special load and speed with its special weighting factor. At each mode, soot emission and engine power were recorded. Brake-specific soot emission was determined as follows (Ghazikhani *et al.* 2008):

$$S_{soot} = \sum_{1}^{13} \frac{\dot{m}_{soot}}{P_{b,s}} \cdot w_f, \tag{1}$$

in which corrected brake power is obtained using the following equation:

$$P_{b,s} = C_f \cdot \frac{2 \cdot \pi \cdot N \cdot T}{60 \cdot 1000}, \tag{2}$$

where: C_f is the power correction factor which is presented by Heywood (1988) as follows:

$$C_f = \frac{P_{s,d}}{P_m - P_{m,v}} \cdot \left(\frac{T_m}{T_S}\right)^{\frac{1}{2}}. \tag{3}$$

The mass flow rate of soot is obtained as follows:

$$\dot{m}_{soot} = \rho_{soot} \cdot 10^{-3} \cdot \dot{Q}_e \cdot 3600, \tag{4}$$

in the above relation ρ_{soot} is the exhaust soot density.

$\dot{Q}_e$ is the volumetric flow rate of exhaust gas and is defined as:

$$\dot{Q}_e = \frac{\dot{m}_a + \dot{m}_f}{\rho_e}, \tag{5}$$

where: ρ_e is the exhaust gas density, which is calculated as:

$$\rho_e = \frac{P_e}{0.287 \cdot (T_e + 273)}, \tag{6}$$

where: P_e and T_e are the exhaust pressure and temperature, respectively, and were measured in the experiments.

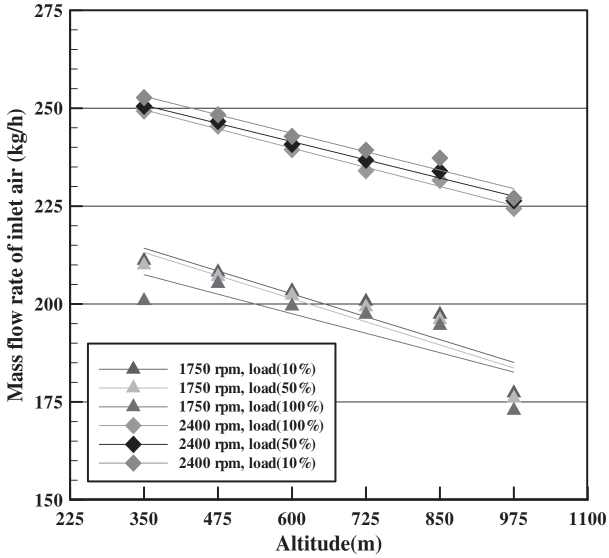

Fig. 2. Effect of altitude on mass flow rate of inlet air

Air mass flow rate was measured by means of an orifice with the discharge coefficient C_d and with the area A_0 using the following equation:

$$\dot{m}_a = C_d \cdot A_0 \cdot \sqrt{2 \cdot 9.81 \cdot \rho_l \cdot \Delta h_{orifice} \cdot \rho_{air}}. \qquad (7)$$

Therefore, the volumetric efficiency of the cylinder at a given environmental temperature and pressure is defined by the following equation (Heywood 1988):

$$\eta_v = \frac{m_a}{\rho_{air} \cdot V_d}, \qquad (8)$$

where: m_a corresponds to the amount of air mass which is charged into the cylinder in each cycle; ρ_{air} is the air density at the intake manifold; V_d is the displacement volume of the cylinder.

Fuel mass flow rate can be calculated as:

$$\dot{m}_f = \frac{50 \cdot 10^{-6}}{t_f} \cdot \rho_f, \qquad (9)$$

where: ρ_f is fuel density that was equal to 830 kg/m^3; t_f is the required time for consumption of 50 cc of fuel.

4. Results and discussions

The analysis of the recorded data is provided as follows:

– *Inlet air mass flow rate.* The effect of altitude on the mass flow rate of inlet air is shown in Figure 2. It declares that the mass flow rate of inlet air decreases with the increase of altitude due to reduction of the pressure and, hence, the density of the inlet air at high altitudes. When the engine speed is low (1750 rpm), the inlet air mass flow reduces by 20% with the increase of the altitude from 350 to 975 m. The figure also reveals that with the increase of the engine speed up to 2400 rpm the percentage of reduction would be about 10%.

– *Volumetric efficiency.* Figure 3 illustrates the variations of volumetric efficiency with altitude at different loads and speeds of engine. As can be seen, changes of the volumetric efficiencies with altitude are insignificant. Although the reduction of the amount of induced mass with increasing altitude was more considerable, the results showed an unimportant reduction in the volumetric efficiency. As introduced in Eqn (8), the volumetric efficiency is defined as the ratio of actual inlet air mass flow arriving to the cylinder to the ideal mass of air which can occupy the displaced volume of the cylinder with the same air density of the induced air. This definition reveals that with increasing the alti-

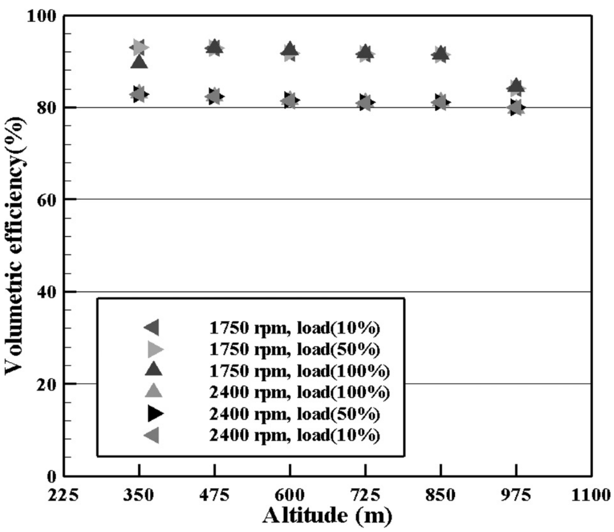

Fig. 3. Effect of altitude on volumetric efficiency

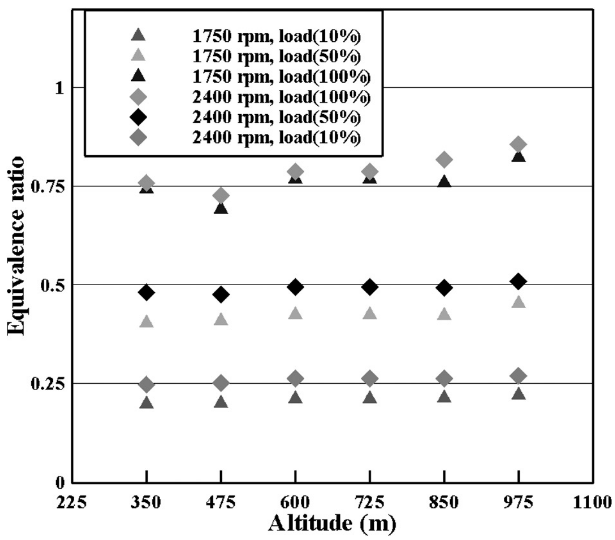

Fig. 4. Effect of altitude on equivalence ratio

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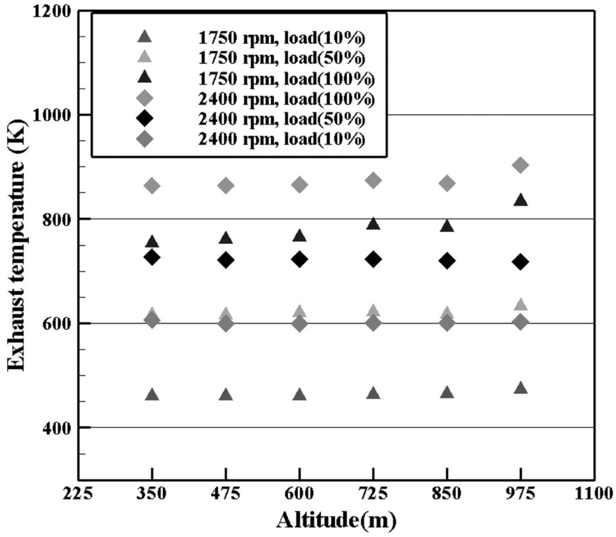

Fig. 5. Effect of altitude on exhaust temperature

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tude, the air mass flow and the air density are changing in the same direction. Therefore, the volumetric efficiency remained approximately unchanged. The minor reduction of volumetric efficiency at high altitudes is probably caused by the heating effect of cylinder walls which prevents enough amount of air to be charged into the cylinder. As Figure 3 shows, with increasing the speed from 1750 to 2400 rpm, the volumetric efficiency is reduced. In fact, this might be due to a rise of the frictional losses of inlet air flow in higher engine speed and the influence of purged gases (residual gas) in the cylinder.

– *Equivalence ratio*. The effect of altitude on equivalence ratio, the ratio of stoichiometric to actual combustion air, is shown in Figure 4. The maximum equivalence ratio occurs at full-load operating condition of engine in both speeds. The equivalence ratio increases in general with increasing the altitude due to the reduction of mass flow rate of inlet air at higher altitude.
– *Exhaust Temperature.* Figure 5 shows the variations of exhaust temperature with altitude. According to Figure 5, the effect of altitude change on exhaust temperature seems to be different in high and low equivalence ratios (high and low engine loads). In higher equivalence ratios where the excess air is lower, increasing altitude can increase the exhaust temperature. It lies within the fact that the same combustion heat release can considerably increase the temperature of the product gases. On the contrary, in low equivalence ratio conditions where there is an abundant amount of excess air in the combustion chamber, increasing altitude which is corresponding to reducing air flow mass can slightly affect the exhaust temperature.
– *Brake-Specific Fuel Consumption (BSFC)*. As Figure 6 shows, BSFC increases about 20% at low load of engine (10% load) with increasing the altitude, despite the fact that for high loads the increment of BSFC is insignificant. These variations can specifically be explained via the effect of intake pressure on the Brake Mean Effective Pressure (BMEP). Engine operation at low loads is tightly dependent on the altitude since the inlet manifold pressure can directly affect the amount of air mass induced into the cylinder. Hence, by increasing altitude, lower amount of air would be introduced to the cylinder and BMEP decreases which implies more fuel consumption for the same amount of output power. When the engine is under higher loads, more amount of fuel is injected into the cylinder which extracts a major portion of induced air internal energy to evaporate. This means that the extra amount of introduced

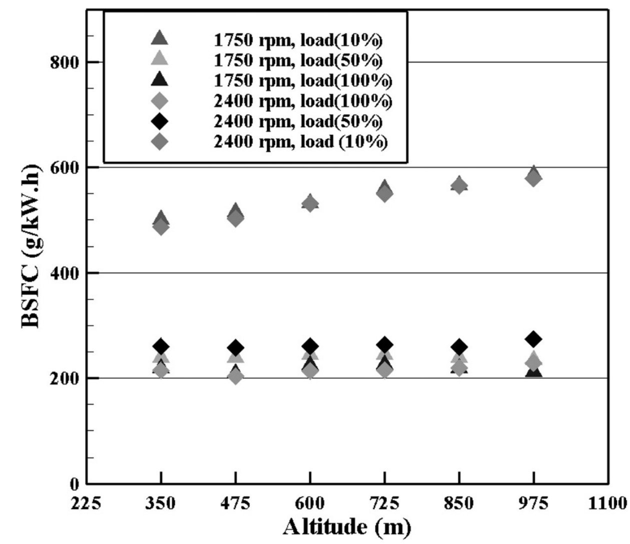

Fig. 6. Effect of altitude on BSFC

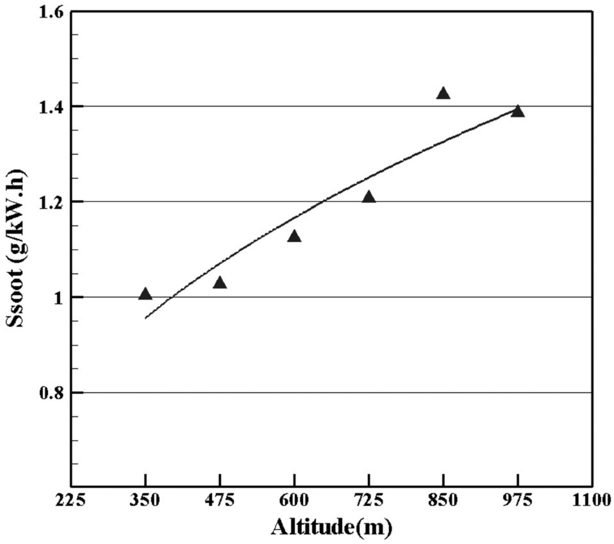

Fig. 7. Effect of altitude on soot emission

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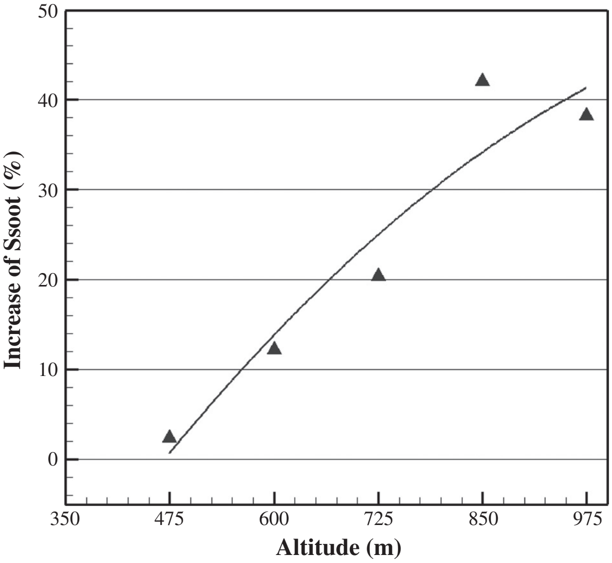

Fig. 8. Percent of increase of brake-specific soot emission with altitude

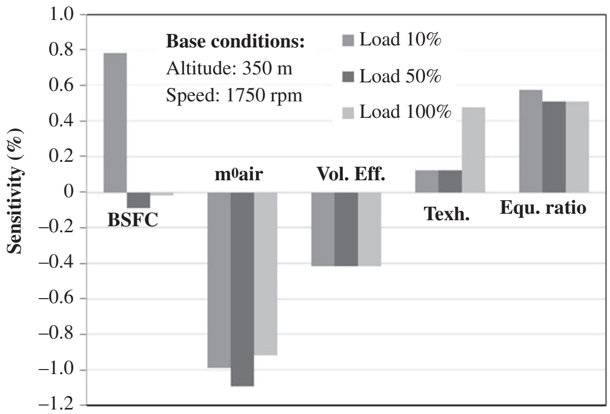

Fig. 9. Results of sensitivity analysis: speed = 1750 rpm for the increase of 35 m of the altitude

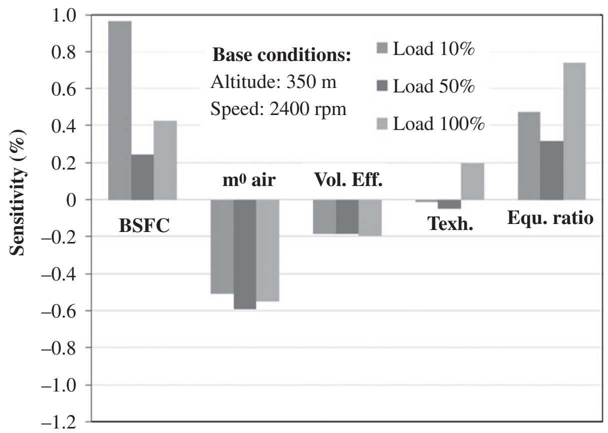

Fig. 10. Results of sensitivity analysis: speed = 2400 rpm for the increase of 35 m of the altitude

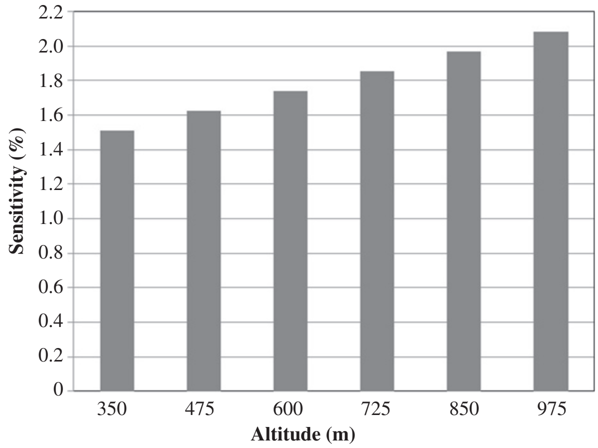

Fig. 11. Sensitivity of specific soot emission at the ECE-R49 standard test to the increase of 35 m of the altitude

mass occurring by decreasing altitude can no longer serve as an increasing factor for BMEP. Thus, this issue can offset the effect of the inlet manifold pressure on BMEP and as a consequence, the BSFC would be almost unchanged at higher loads. It is also observed in Figure 6 that the minimum fuel consumption is occurred at the maximum load and speed of the engine. Because, at high loads and speeds, the frictional losses in the engines are not increased with power output proportionally.

– *Soot emission*. The altitude effect on brake-specific soot emission is indicated in Figure 7. As known, soot emission is generated when the air–fuel mixture is incompletely combusted. When the engine is operating at higher altitudes, lesser amount of air is introduced into the cylinders, causing the air–fuel mixing process to deteriorate in the higher altitudes. This conclusion is supported intuitively in that more collisions, and therefore, higher reaction rates, will occur as pressure increases and the unburned soot decreases due to better oxidization. Lowering oxygen concentration by increasing altitude increases untimely and incomplete combustion in the engine cylinders which lowers fuel conversion efficiency and causes the exhaust soot emission to increase. In the experiments, it was observed that as altitude increases from 350 to 975 m, the amount of soot emission increases almost about 40%, as is illustrated in Figure 8.

5. Sensitivity analysis

A sensitivity analysis was carried out in order to show the most sensitive engine parameters to the altitude changes. Figures 9 and 10 display the results of sensitivity analysis for different engine parameters where the base altitude in the analysis was selected at the 350 m above sea level. This analysis was conducted by considering an absolute increase of 10% of altitude (35 m) where different speeds and loads of the engine can be chosen separately as base conditions. As can be seen, the percentages of sensitivity with 35 m increasing of altitude are as follows.

Mass flow rate of air is reduced (0.5÷1.1%), BSFC is increased (0÷1%), equivalence ratio is increased (0.3÷0.7%), volumetric efficiency is reduced (0.2÷0.4%), and exhaust temperature is increased (0.1÷0.5%). Figure 11 also shows the ECE-R49 specific soot emission sensitivity calculation with 35 m increasing of altitude at different altitude position; the figure reveals that specific soot is increased (1.5÷2.1%). It was found from the sensitivity analysis that the most sensitive engine parameter is the specific soot emission and the other parameters like mass flow rate of air, equivalence ratio, BSFC, volumetric efficiency and exhaust temperature have less sensitivity to altitude, respectively.

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Conclusions

The effect of altitude on exhaust soot emission of a DI-diesel engine was investigated experimentally by considering the ECE-R49 test cycle.

The experiments were carried out at an altitude of 975 m above sea level. The reduction of altitude to 350 m was simulated by increasing the inlet manifold pressure via a Roots air blower which was coupled with the engine flywheel. It was found that an increase in altitude from 350 to 975 m is caused by an increase of 40% in the exhaust soot emission due to decreasing the density of inlet air and, hence, more incomplete combustion.

The results showed an insignificant reduction in the volumetric efficiency, while the amount of decreasing mass flow rate of inlet air was considerable with increasing altitude. With increasing altitude, BSFC considerably increases at low engine loads. However, at high engine loads, BSFC barely changes. Equivalence ratio increases at higher altitudes due to lower inlet air mass flow. Despite this change, the exhaust temperature scarcely rises due to more fuel/air ratio.

From the sensitivity analysis, it can be concluded that among the engine parameters, the soot emission has the highest sensitivity to the altitude variations.

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