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Original Paper

Effects of air throttling on the performance and emission characteristics of a diesel engine

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Abstract: The air-fuel ratio is a significant parameter related to engine performance, and can be controlled by adjusting the throttle valve and the amount of fuel injected. In this study, the performance and emission characteristics of an air-cooled single-cylinder MITSUKI MIT-178F diesel engine were investigated by imposing varying loads on the air throttling levels of 65%, 70%, and 75%. Accordingly, the torque generated by the engine increased as the air throttling level increased, and the fuel conversion efficiency was very low for the cases with air throttling levels of 65% and 70%. It was observed that the higher the exhaust gas temperature, the higher the NO_x emission, and the lower the CO_2 emission concentration as the engine speed increased. In addition, particulate matter (PM) concentration appeared to decrease as the air-fuel ratio increased under air throttling levels of 70% and 75%.

Keywords: Air-fuel ratio, Fuel conversion efficiency, NOx, PM, CO_2

1. Introduction

Diesel engines have been widely utilized as power sources for land transportation, ships, and construction machinery because of their high thermal efficiency. However, there is a disadvantage because harmful emissions such as nitrogen oxides (NO_x) and particulate matter (PM) are generated, owing to the high combustion temperature and chemical reaction of the inhomogeneous fuel-air mixture. To satisfy environmental regulations, the research on dual-fuel engines for ships continues, and efforts are made to optimize performance and efficiency, such as adjusting the common rail pressure. In addition, research to reduce the emission of harmful substances by the improvement and optimization of combustion methods, such as multi-stage injection, has been actively conducted **[1]-[2]**.

To reduce NO_x emissions, it is important to lower the combustion temperature inside the combustion chamber. Accordingly, other fuels or substances can be mixed with the existing diesel fuel **[3]**. When methanol is utilized as a fuel additive, the oxygen content in the fuel increases, the heat of evaporation increases, and NO_x and PM during combustion tend to decrease **[4]**. Emulsified fuel, in which water is added to diesel fuel, reduces the internal temperature of the combustion chamber as water evaporates first during the combustion process **[5]-[6]**. In addition to these approaches, NO_x emissions can be reduced by using after-treatment technologies, such as selective catalyst reduction (SCR) or lean NO_x trap (LNT). Urea-SCR separates the NO_x contained in the exhaust gas into nitrogen and water, by utilizing NH_3 generated through thermal decomposition and hydrolysis of urea as a reducing agent. LNT absorbs NO_x under lean conditions and reduces NO_x to N_2 by supplying a reducing agent by an in-cylinder post-injection under rich conditions **[7]-[9]**.

In addition, it is possible to improve engine performance and reduce the emission of various harmful substances by controlling the air-fuel ratio related to the formation of a mixture inside the combustion chamber, which can be done by regulating the air-throttle and exhaust gas recirculation (EGR) valves. Because the intake pressure of the air flowing into the combustion chamber affects the performance and concentration of exhaust gases, the turbocharger application is preferred over the naturally aspirated method, and the performance and efficiency of the engine can be improved by improving the efficiency of the turbocharger **[10]-[15]**.

In this study, to investigate the effect of air throttling on the performance and emission characteristics of a naturally aspirated

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single-cylinder diesel engine, an experiment was conducted by gradually altering the load for three different levels of air throttling. Accordingly, the effect of air throttling on the performance and emission characteristics of MITSUKI's MIT-178F diesel engine was investigated under a wide range of operating conditions, and a database for future parametric studies was established.

2. Experimental setup and method

Figure 1 is a schematic diagram of the MT502E PC-controlled single-cylinder engine testbed and exhaust gas measurement devices. The main specifications of the engine are presented in **Table 1**. The engine load and air throttling level can be controlled by a control box connected to a PC, thereby indirectly altering the air-fuel ratio. Significant physical quantities, including power and specific fuel consumption, and output are automatically calculated using a built-in software. The concentration of different species in the exhaust gas must be measured using a separate device. QROTECH's OPA-102 smoke meter was utilized to measure the concentration of PM, and QROTECH's QRO-402 gas analyzer was utilized to measure the concentration of significant emissions such as NO_x and CO.

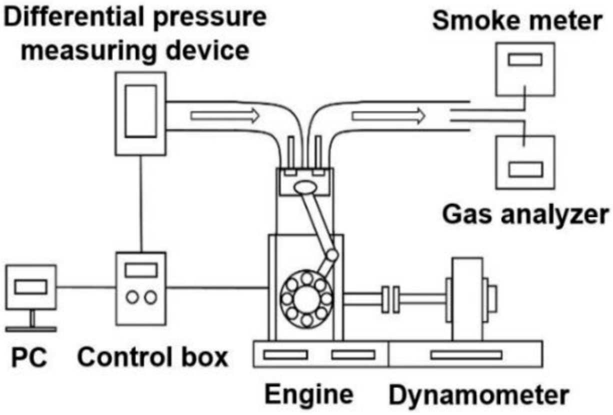


Figure 1: Schematic diagram of the experimental apparatus

Table 1: Specifications of the MITSUKI diesel engine

Model	MIT-178F
Maximum horsepower/ Engine speed	7.0 HP/3000rpm
Engine type	Single-cylinder, 4-stroke
Cylinder volume [cc]	305
Cooling system	Air-cooled type
Combustion system	Direct injection
Fuel type	Diesel

To investigate the performance and emission characteristics of a diesel engine by air throttling, 12 experimental conditions were tested, as presented in **Table 2**. The experiment was conducted at 1 atm and 18 °C, however, because it is an air-cooled type engine, a coolant was not utilized. The load was increased after setting the air throttling level by the PC connected to the control box for each experimental condition. At this time, as the load increased, the engine speed decreased, and the engine stopped when the specific load level was exceeded for a given air throttling level. Therefore, it is necessary to determine the operable load range according to the air throttling level by trial and error.

The manufacturer recommended testing at an air throttling level of 80% or lower; hence, pilot tests were conducted between 50% and 85%. However, at air throttling levels above 80%, the engine vibration was excessive. In addition, in conditions where the air throttling level was below 65%, the operating engine speed range was too narrow to establish various test conditions. Therefore, three air throttling levels of 65%, 70%, and 75% were chosen, and for each air throttling level, the engine speeds were set at an interval of 125 rpm. Adjusting the air throttling level altered the amount of air flowing into the combustion chamber; hence the air-fuel ratio for each condition was different.

After the engine reached a statistically steady state for each experimental condition, the data were sampled at intervals of 5 s for approximately 1 min, and the average was calculated. The maximum standard deviation was approximately 0.05 and 0.01 for torque and brake power, respectively, and the maximum standard deviation for CO, CO_2, and PM concentrations measured in percent was approximately 0.04. Regarding HC and NO_x concentrations measured in ppm, the maximum standard deviation was 3.3.

The MT502E testbed of the ESSOM facilitates the control of limited parameters, so there is a limit to performing parametric studies on other significant operating conditions. Therefore, the use of a numerical method for a detailed parametric study of a specific variable may be better.

Table 2: Test cases

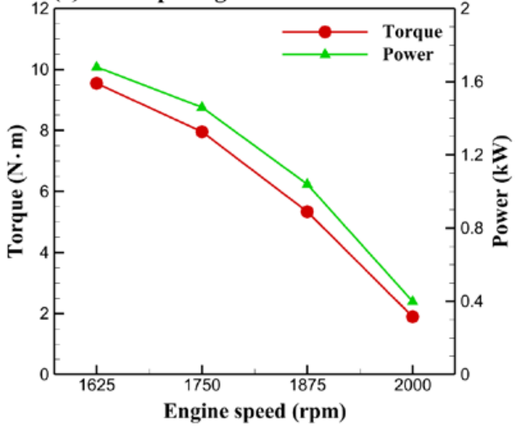
Air throttling level [%]	Engine speed [rpm]			
65	1625	1750	1875	2000
70	1875	2000	2125	2250
75	2125	2250	2375	2500

3. Results and discussion

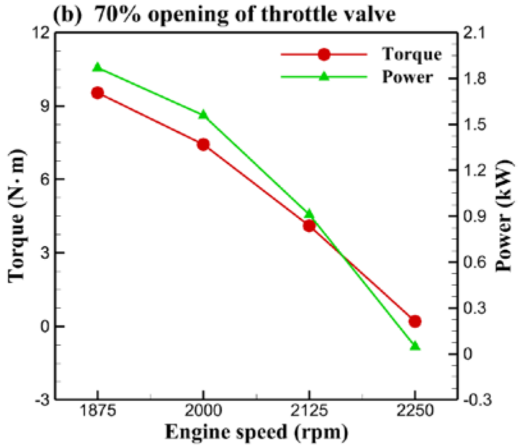
3.1 Engine performance and fuel conversion efficiency

Figure 2 illustrates the torque and brake power of the engine, which are the main indicators in the evaluation of the engine performance. In the test engine, as the air throttling level increased, the torque generated by the engine and the maximum engine speed increased, and for a given air throttling level, the torque generally decreased as the engine speed increased. This was because of the method of controlling the engine speed, which means that as the load increased, the engine speed decreased.

(a) 65% opening of throttle valve



(b) 70% opening of throttle valve



(c) 75% opening of throttle valve

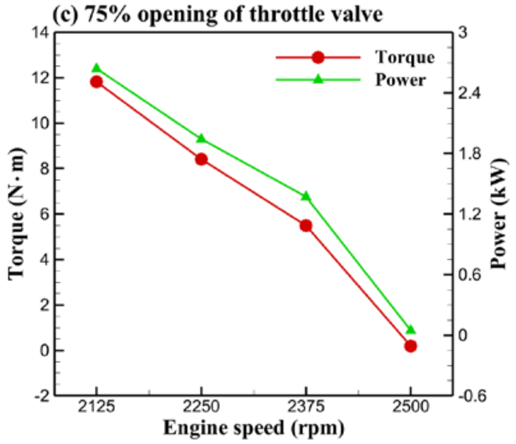


Figure 2: Torque and brake power with engine speed

For all air throttling levels, the torque and brake power decrease more rapidly in the region of high engine speed, which in turn led to a decrease in the fuel conversion efficiency of the engine. **Figure 3** illustrates the fuel conversion efficiency defined by **Equation (1)**.

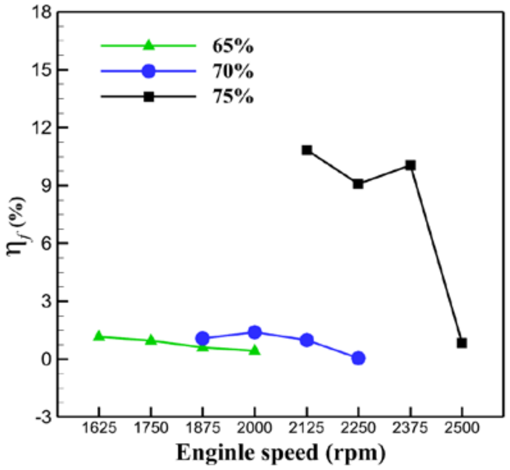


Figure 3: Fuel conversion efficiency (η_f) with engine speed

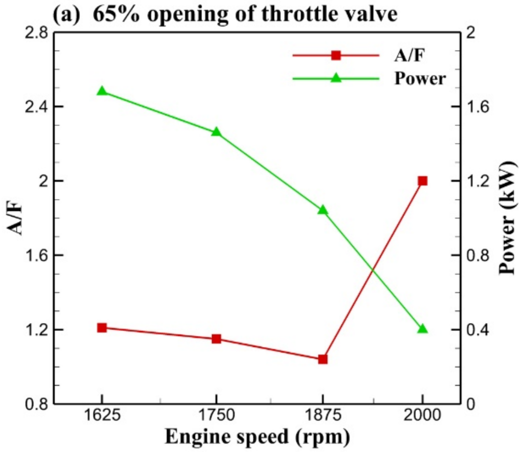
$$\eta_f = \frac{P}{\dot{m}_f Q_{LHV}} \tag{1}$$

where P is the power, Q_{LHV} is the low heating value of the fuel, and $\dot{m}_f$ is the rate of fuel consumption.

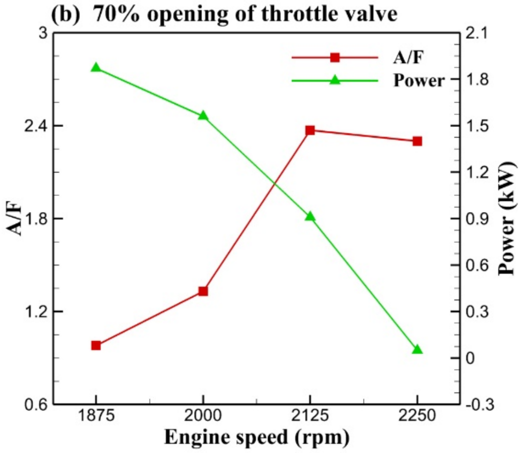
Under the experimental conditions with air throttling levels of 65% and 70%, the fuel conversion efficiency was very low, and the efficiency decreased as the engine speed increased. However, the efficiency of the air throttling level of 75% was approximately 5–6 times higher than that of the other conditions. It is desirable to understand that the rapid increase in fuel conversion efficiency because of the air throttling level, is a unique characteristic of the test engine. It can be inferred that the condition for optimal engine efficiency to occur is set to approximately 75% of the air throttling level, and it indicates that the conditions leading to the maximum power of the engine and the maximum fuel conversion efficiency are not similar.

From the experimental results with an air throttling level of 75%, a fuel conversion efficiency of approximately 8%–11% was observed in the region where the engine speed increased from 2125 rpm to 2375 rpm, but there was no clear trend with the engine speed. However, the engine power indicated a steady decrease from 2.6 kw maximum to 1.3 kw in a similar engine speed region.

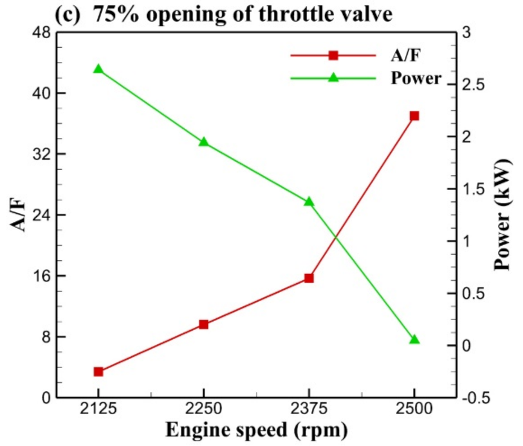
Figure 4 illustrates the air-fuel ratio and engine power with engine speed. The air-fuel ratio indicates the mass ratio of air and fuel utilized for combustion. The larger the air-fuel ratio, the



(a) 65% opening of throttle valve



(b) 70% opening of throttle valve



(c) 75% opening of throttle valve

Figure 4: Air-fuel ratio and brake power with engine speed

leaner the gas; conversely, the lower the air-fuel ratio, the richer the gas. The tendency of the air-fuel ratio with engine speed is unclear at the air throttling level of 65%, and it is difficult to confirm the correlation between the air-fuel ratio and engine power. At an air throttling level of 70%, except the 2250 rpm condition, the air-fuel ratio increased, while the power decreased as the engine speed increased, i.e., as the load decreased. The opposite trends between the air-fuel ratio and engine power were observed under all conditions at 75% air throttling, because the engine speed increased as the engine load decreased.

Table 3 presents the amount of air intake and fuel injection measured for all the test cases. A high air-fuel ratio does not mean that there is a significant amount of air intake. In addition, in the case of the engine testbed utilized in this study, the amount of fuel injection increased as the load increased under air throttling levels of 70% and 75%, and the air-fuel ratio decreased accordingly.

Table 3: Air-fuel ratio with engine speed

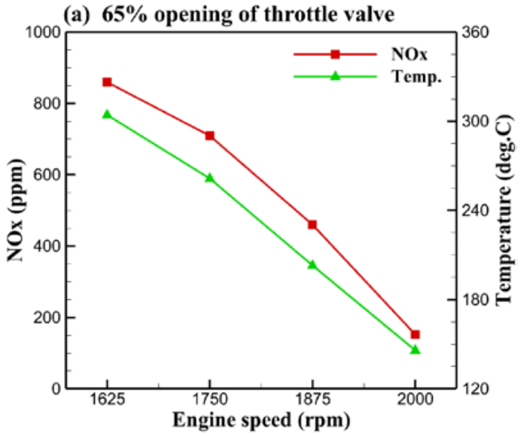
Air throttling [%]	RPM	A/F	m_a [kg/h]	m_f [kg/h]
65	2000	2.00	17.91	8.95
	1875	1.04	17.09	16.50
	1750	1.15	16.23	14.12
	1625	1.21	15.73	12.96
70	2250	2.30	18.82	8.19
	2125	2.37	18.20	7.69
	2000	1.33	17.38	13.02
	1875	0.98	16.52	16.79
75	2500	36.99	19.42	0.53
	2375	15.68	18.44	1.18
	2250	9.62	17.72	1.84
	2125	3.41	17.20	5.05

3.2 Emissions

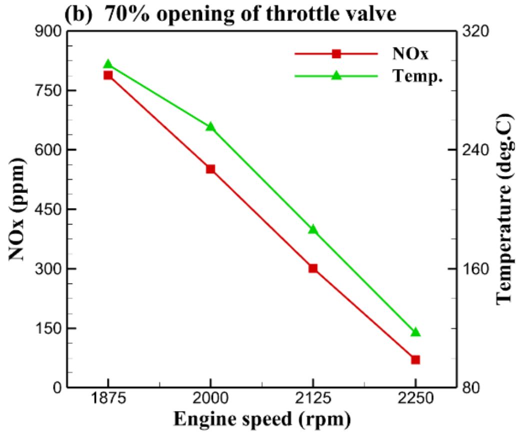
Figure 5 illustrates the measured NO_x concentrations and exhaust gas temperatures. As the air throttling level increases, the NO_x concentration decreases. The NO_x emission tends to decrease at a given air throttling level as the exhaust gas temperature decreases. A similar tendency of exhaust gas temperature and NO_x emissions indicates that the portion of thermal NO_x is high.

Figure 6 illustrates NO_x, HC, CO_2, CO, and PM concentrations for all experimental conditions. **Figure 6(a)** illustrates that the concentration of NO_x is lowest at each throttling when the engine load is the smallest, i.e., when the engine speed is the highest. **Figure 6(b)** illustrates that the concentration of HC is independent of the air throttling level, and the correlation between the concentration of HC and the engine speed is unclear. Therefore, HC generation is presumed to result from incomplete combustion near walls or crevices, rather than operating conditions such as air throttling. **Figures 6(c)** and **(d)** illustrate the concentrations of CO_2 and CO. For different air throttling levels, the concentration of CO_2 tends to decrease as the engine speed increases, but the concentration of CO does not exhibit a clear correlation. CO is the intermediate product before the generation of the

(a) 65% opening of throttle valve



(b) 70% opening of throttle valve



(c) 75% opening of throttle valve

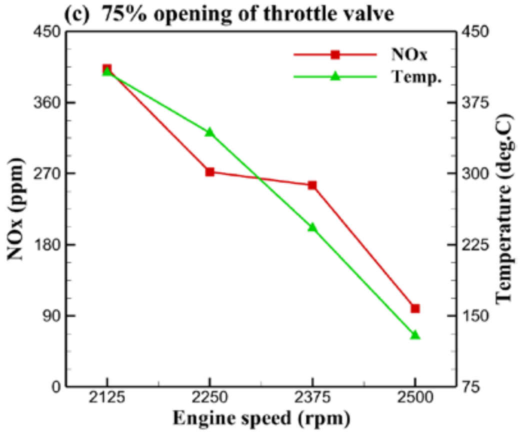


Figure 5: Measured NO_x and exhaust gas temperatures with engine speed

final product CO_2 in a combustion process. Unlike gasoline engines, diesel engines generally operate under fuel-lean conditions. The concentration of CO measured in this experiment is less than that of CO_2 by five orders of magnitude, so it is difficult to consider the CO emission to be significant.

Figure 6(e) illustrates the tendency of the PM concentration to decrease as the engine speed increases for different air throttling levels. From **Figure 4** and **6(e),** it can be inferred that the PM concentration decreases as the air-fuel ratio increases for air throttling levels of 70% and 75%. This means that PM emissions are reduced as sufficient air is supplied to the combustion chamber; hence, incomplete combustion near the flame surface is reduced.

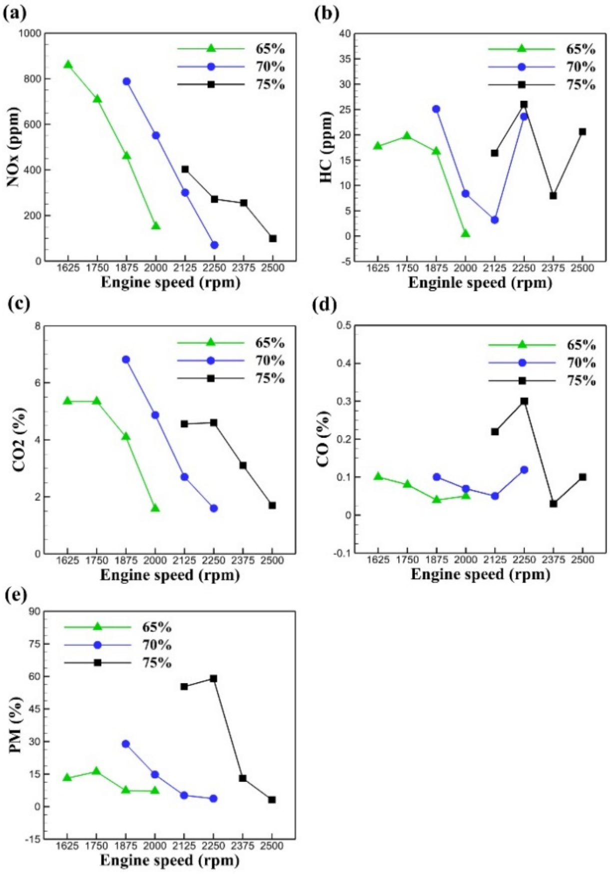


Figure 6: Emissions with engine speed

4. Conclusion

The effects of air throttling on the performance and emission characteristics of the MITSUKI MIT-178F diesel engine were investigated under 12 experimental conditions, and the following results were obtained.

(1) As the air throttling level increased, the torque generated by the engine increased , and for a given air throttling level, the torque generally decreased as the engine speed increased.

(2) The fuel conversion efficiency was very low at air throttling levels of 65% and 70%, and there is a common tendency that the fuel conversion efficiency decreased as the engine speed increased at different air throttling levels.

(3) At 65% air throttling, there is no clear correlation between the air-fuel ratio and the power; however, at 70% and 75% air throttling, the air-fuel ratio increased, while power

appeared to decrease as the engine speed increased.

(4) The higher the exhaust gas temperature, the higher the NO_x emissions, which means that the higher the proportion of thermal NO_x.

For different air throttling levels, the concentration of CO_2 decreased as the engine speed increased, and the concentration of PM appeared to decrease as the air-fuel ratio increased for air throttling levels of 70% and 75%.

Author Contributions

Conceptualization, C. O. Park and J. Kwon; Writing—Review & Editing, B. Kim and J. Kwon; Visualization, C. O. Park; Supervision, J. Kwon.

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