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Int. J. Therm. Sci. 41 (2002) 63–71

International Journal of Thermal Sciences

# Effect of air injection on the characteristics of transient response in a turbocharged diesel engine

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Received 12 October 2000; accepted 22 February 2001

**Abstract**

An experimental study was performed to investigate the improvement of transient characteristics of a turbocharged diesel engine under the conditions of low speed and fast acceleration with the load. In this study, the experiment for improving the low speed torque and acceleration performance is performed by means of injecting air into the intake manifold during the period of low speed and application of a fast acceleration. The effects of air injection into the intake manifold on the response performance are investigated at various thermodynamic parameters such as air injection pressure, air injection period, accelerating rate, accelerating time, engine speed and load. The experimental results show that air injection into the intake manifold at compressor exit is closely related to the improvement of low speed and acceleration performance of a turbocharged diesel engine. During the rapid acceleration period, the air injection into the intake manifold of turbocharged diesel engine indicates the improvement of the combustion characteristics and gas pressure in the cylinder. At low speed range of the engine, the effect of air injection shows the improvement of the pressure distribution of turbocharger and combustion pressure during the period of gas exchange pressure. 

*Keywords:* Turbocharged diesel engine; Rapid acceleration; Air injection effect; Transient response performance; Turbocharger performance

## 1. Introduction

The power output of a diesel engine is directly related to the amount of fuel burnt in cylinder. The power produced by an engine depends on the quantity of intake air available. In a diesel engine, the extra air is supplied to burn more fuel, and this is provided by the external supply of turbocharger. One of the methods for improving engine power performance is to use the turbocharger, which is driven by the exhaust gas from the engine cylinders.

A turbocharged diesel engine has good characteristics that can improve fuel consumption rate, exhaust emissions, and the increase of specific power output of the engine.

In order to increase the power output and to save the energy, the turbocharged diesel engines are usually used for automotive engines. But these engines occur turbocharger lag during the transient condition such as a rapid acceleration or a sudden large load application, and then result in a worse response performance than those of naturally aspirated engine. By the adopting the turbocharged diesel engine, the maximum thermal efficiency is increased, while turbo charged vehicle has a weak point of poor drivability under transient running conditions when the turbocharger does not work effectively, especially at low speed operation and rapid acceleration by the control of fuel-pump rack. Quick changes in rack position do not result in instantaneous response of the turbocharger, due to its inertia and compressibility of the exhaust gas with the engine. Thus the air-fuel ratio quickly decreases to a very low value and the mixture occurs incomplete combustion; although much quantity of fuel can be rapidly injected into the cylinders, the turbocharger is slow to respond and provide a corresponding increase in air for the combustion. For this reason, a study on the investigation and the improvement of transient performance is to be a very important subject [1]. Numerous studies for the improvement of the transient response of turbocharged diesel engines are focused on the optimum design and control of turbocharger [2,3]. Also, the improvement of turbocharger performance and the transient characteristics of diesel engine have studied by many researchers [4–6].

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1290-0729/02/$ – see front matter 
PII: S1290-0729(01)01304-7

**Nomenclature**

| | | |
|---|---|---|
| Comp | compressor | |
| $L$ | load | Nm |
| $n$ | engine speed | rpm |
| $P$ | pressure or pressure transducer | bar |
| $P_{air}$ | air injection pressure | bar |
| $P_{cyl}$ | cylinder pressure | bar |
| $R$ | air pressure regulator | |
| $T$ | temperature or thermometer | K |
| Turb | turbine | |
| $T_{in}$ | turbine inlet temperature | T |
| Acc.time | the time of rapid acceleration | sec |
| Acc.rate | the rate of rapid acceleration | % |
| AVO | air valve open | |
| EVO | exhaust valve open | |

Considerable work has been done dealing with the transient characteristics and influencing factors for the diesel engine with a turbocharger such as acceleration performance, starting stability, sudden large load, and the speed range of the engine [7–10]. Most of previous papers have described the simulation studies of the matching of turbocharger and transient performance of turbocharged diesel engine. However, the experimental works for the improvement of response characteristics are scarcely reported [11,12].

In the turbocharged engine, the thermodynamic intensive parameters such as gas pressure and temperature in the engine, turbocharger conditions (pressure and temperature), pressure fluctuation of intake and exhaust process of gas exchange period, and many factors have influenced on the total performance of the engine.

During the transient operation, the improvements of these transient performances can be achieved both by controlling the fuel flow and supplying air into the cylinder by some external system.

The purpose of this work was to investigate the effect of air injection into the intake manifold near the intake port at the compressor exit on the thermodynamic intensive properties of engine and turbocharger during the rapid acceleration of the low speed range in the turbocharged diesel engine. Also, the improvement of transient response of turbocharged diesel engine has investigated by means of air injection into the intake manifold at the compressor exit. The effect of air injection into the intake manifold on the factors of response performances such as turbine inlet pressure, compressor exit pressure, combustion pressure and the engine speed are discussed.

## 2. Experiments

### 2.1. Experimental apparatus

Fig. 1 shows a schematic diagram of the turbocharged engine test apparatus and measuring system. The test rig is equipped with a 150 kW eddy current dynamometer, controlled by the electronic system. An automotive, 2.474 L turbocharged diesel engine was installed in the test apparatus.

The turbocharger of the test engine consists of a radial turbine and centrifugal compressor. The details of the engine and turbocharger are listed in Table 1. As shown in Fig. 1, the experimental apparatus is composed of the

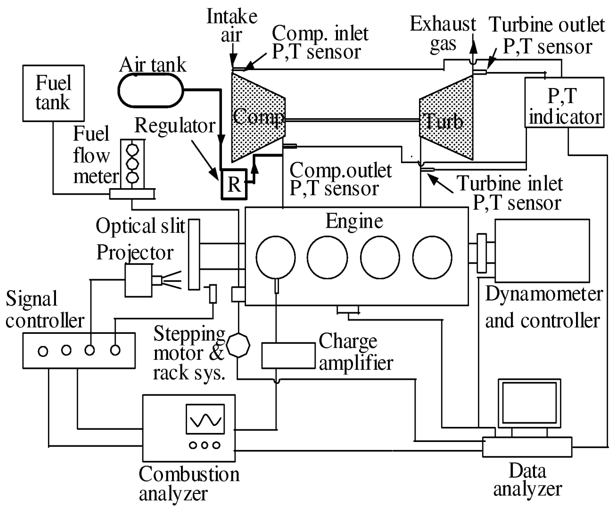



Fig. 1. Schematic diagram of experimental apparatus.

Table 1
Specifications of experimental engine and turbocharger

| Engine and turbocharger | | Specification |
|---|---|---|
| Engine type | | 4 stroke diesel engine |
| Number of cylinder | | 4 |
| Combustion chamber | | Indirect injection |
| Bore × stroke (mm) | | 91.1 × 95.0 |
| Piston displacement (cc) | | 2476 |
| Compression ratio | | 21.1 |
| Connecting rod length (mm) | | 158.4 |
| Maximum power (PS/pm) | | 85/4200 |
| Volume of intake manifold (l) | | 0.00118 |
| Volume of exhaust manifold (l) | | 0.00104 |
| Diameter of turbine blade (mm) | | 39 |
| Valve timing | Intake Open (deg) | BTDC 20° |
| | Close (deg) | ABDC 48° |
| | Exhaust Open (deg) | BBDC 54° |
| | Close (deg) | ATDC 22° |
| Turbocharger | Turbine | Radial type |
| | Compressor | Centrifugal type |

test engine, an eddy current dynamometer, control system of fuel and injection air, and data acquisition system. In this arrangement of test apparatus, the bold solid line is air-supplying line from the air tank to the intake port, and the thin line is the measuring line of transient performance of the engine.

Fig. 2 shows the control system of injection pump rack. Fuel control rack is connected to the pulley fitted to rotating shaft of stepping motor and an reduction gear with gear ratio of 10:1 is used to increase the control of torque. A rapid acceleration is conducted with the rotation of stepping motor that rotates 0.9 degree per pulse, and its pulse is controlled by means of microcomputer. The system of air injection into the intake manifold is composed of the air receiver, regulator valve, timer switch and pipe of air supply. The nozzle for injecting air into the intake manifold is embedded in the hole of 7.6 mm diameter and 3 mm deep, which is drilled at gradient of 30 degree on the surface of compressor delivery pipe. Compressed air is injected into the intake manifold through the air nozzle with diameter of 6 mm.

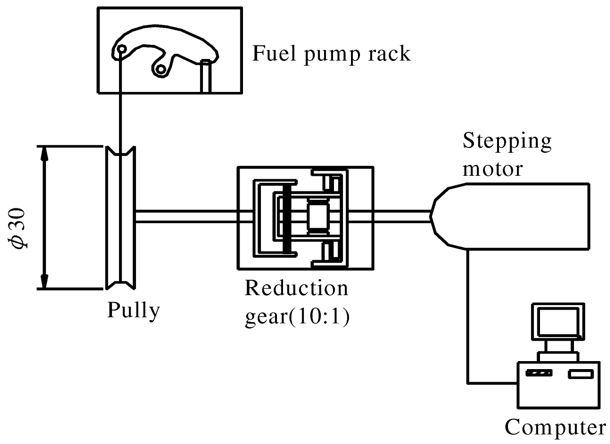



Fig. 2. Acceleration system of fuel-pump rack.

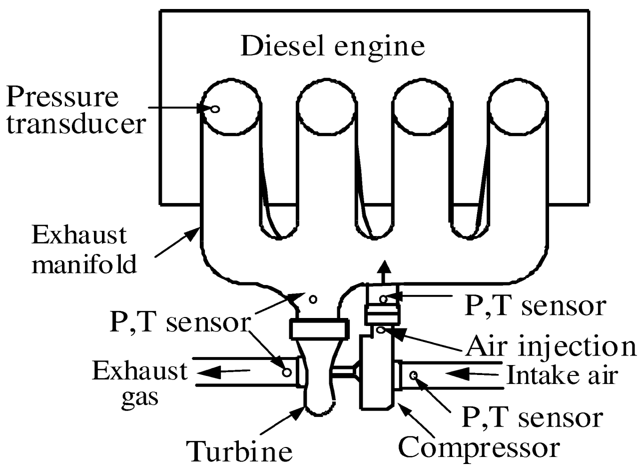



Fig. 3. Arrangement of air injection system.

The arrangements of the engine and turbocharger with air injection system are shown in Fig. 3. Injection time and injection pressure of air are controlled by use of airflow rate controller. Pressure sensors are installed to the compressor inlet and exit, turbine inlet and exit, and No.1 cylinder as shown in Fig. 3.

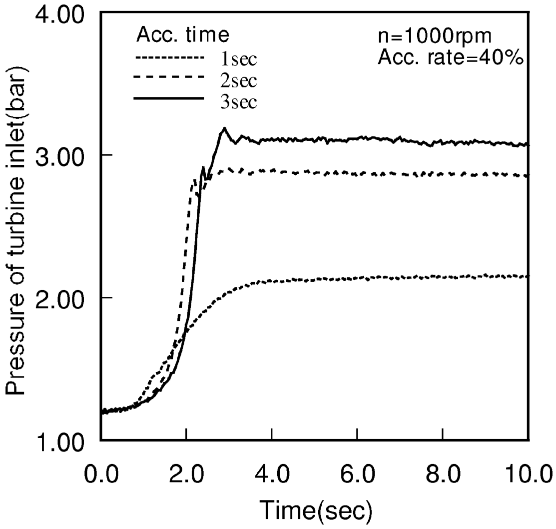
### *2.2. Experimental procedures*

Experiments are carried out at two engine speed of 1000 and 2000 rpm with and without the air injection during the transient conditions of a rapid acceleration, and their results are compared with the response characteristics of a turbocharged diesel engine. The major parameters measured under the transient operating conditions are engine speed, fuel rack position, turbine inlet pressure and compressor exit pressure, and cylinder pressure. The experiments were performed for two cases of steady state and transient state conditions at given load and engine speed. In order to improve the performance of rapid acceleration with the load, the pressure of the injected air and the load are 1–3 bars and the engine load of 163 Nm, respectively. The flow rate of intake air was monitored by an orifice flow meter and controlled with a precision flow control valve. Also, the transient performance of the test engine is compared the experimental results of air injection with that of without air injection. Based on the investigation results, the improvement of transient characteristics is compared with the variations of load and acceleration rate under the air injection. The outputs of sensor elements used for measurement of these parameters are connected with each channel of digital memory, and their data are transferred to a microcomputer. In order to compare the results of steady test and transient investigation, the test are carried out at 1000 rpm and 2000 rpm of engine speed under the full load condition. Also, accelerating test was performed at the same speed with the engine load of 163 Nm.

## 3. Experimental results and discussion

### *3.1. Effect of accelerating time on the response performance of turbine inlet pressure*

In order to investigate the response performance of turbine inlet pressure in a turbocharged diesel engine, the experiment is carried out at various engine conditions with the changes of transient performance factors such as the rate of a rapid acceleration, accelerating time, injection period, injection pressure and engine load. A rapid acceleration is applied to the fuel rack of the engine from 0–10% to 0–40% in steps of 10%, and accelerating time of 1, 2 and 3 seconds is applied to the engine. Injection pressure and injection duration of the air are 3 bars and 1, 3, 5 and 10 seconds, respectively.

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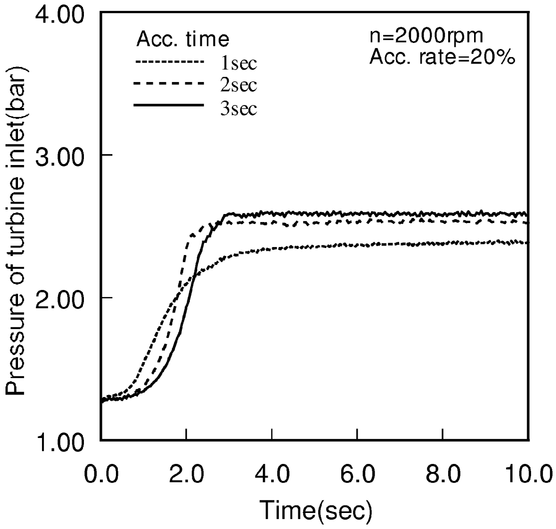


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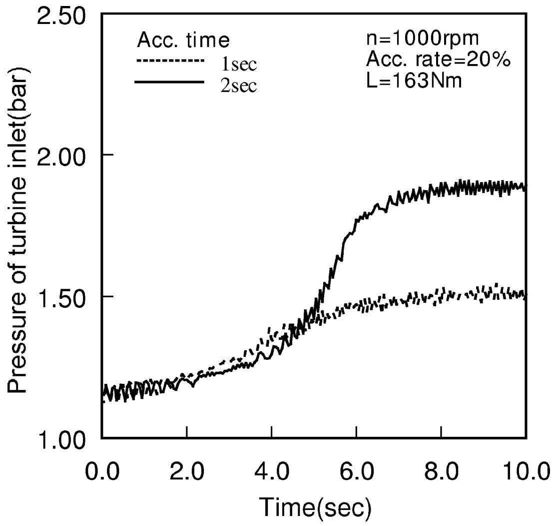
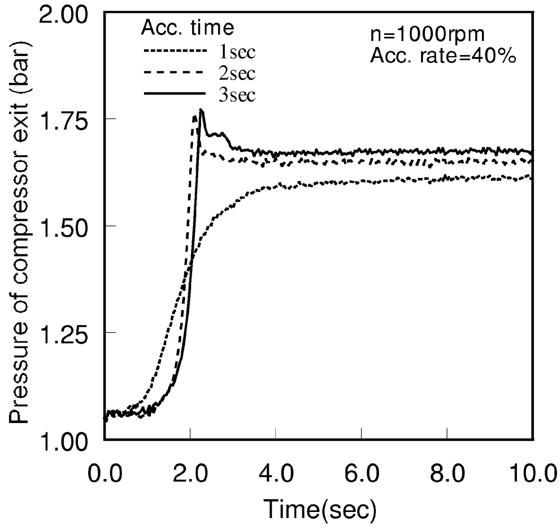
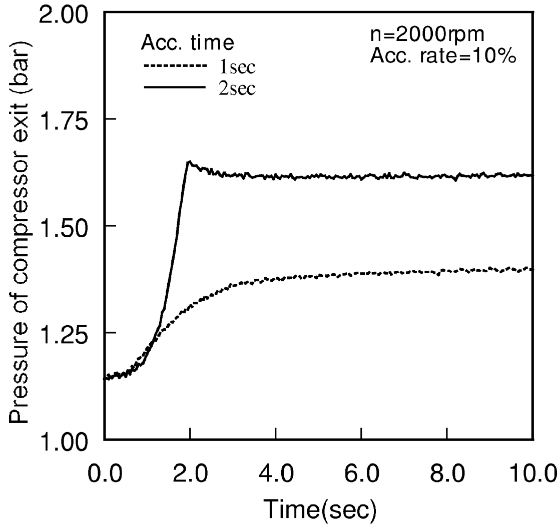



(c)

Fig. 4. Effects of accelerating time on the response performance of turbine inlet pressure: (a) $n = 1000$ rpm; (b) $n = 2000$ rpm; (c) $n = 1000$ rpm (163 Nm).




(a)

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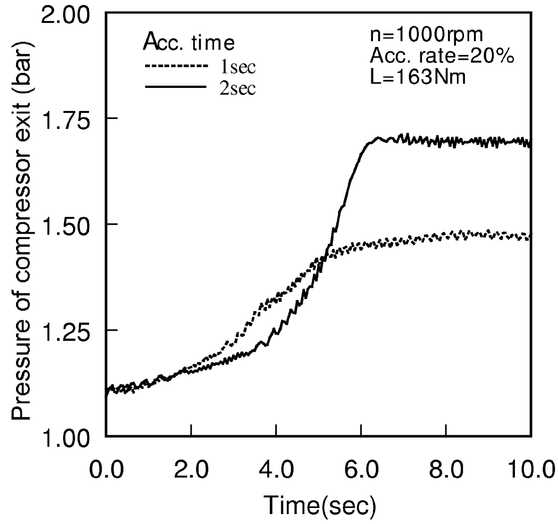


(c)

Fig. 5. Effects of accelerating time on the response performance of compressor exit pressure: (a) $n = 1000$ rpm; (b) $n = 2000$ rpm; (c) $n = 1000$ rpm (163 Nm).

The total length of fuel rack, which can be moved, is 36 mm at 1000 rpm of no load and 26 mm at 1000 rpm of 163 Nm load. In each engine speed, three kinds of acceleration time (1, 2 and 3 seconds) are applied to the test engine.

Figs. 4 and 5 show the influences of accelerating time on the thermodynamic transient response of turbine inlet and compressor exit pressures. As illustrated in figures, turbine inlet and compressor exit pressures are largely increased in accordance with the application of slow accelerating time and reached more quickly to the range of their final steady state pressure. An increase of accelerating time shows the increase of the turbine inlet pressure and the shortening of transient duration.

It is clear from these results that the rapid accelerating time is the main cause of turbocharger lag, which is closely related to the transient response performances of a turbocharged diesel engine The effect of rapid acceleration on the transient performance of turbocharger characteristics shows the slow increasing of turbocharger pressure because of turbocharger lag.

### *3.2. Effect of turbine inlet pressure and engine parameters on the recovery time*

Fig. 6 shows the effect of accelerating rate on the recovery time to steady state of cylinder pressure, engine speed and turbine inlet temperature. The recovery time to steady state of cylinder pressure, engine speed and turbine inlet temperature were increased with the increase of rapid accelerating rate.

As shown in figure, the transient response of the turbocharging factors that affect to the transient performance of test engine are lately recovered in accordance with the increase of the accelerating rate to the steady state of the test engine.

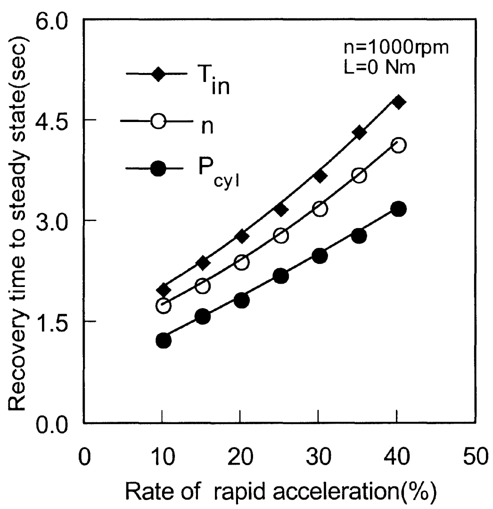


Fig. 6. Relations between a accelerating rate and recovery time.

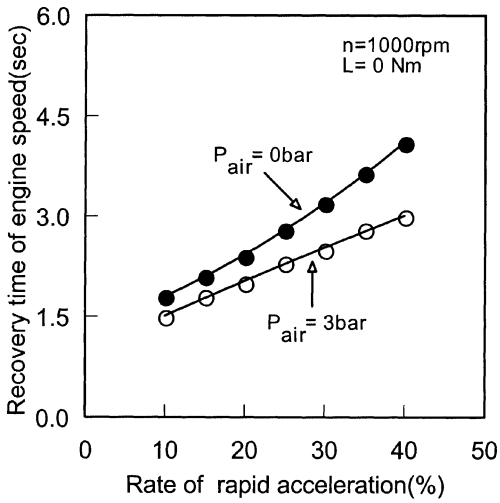


Fig. 7. Effects of air injection on the recovery time.

It is also obvious that as the acceleration is applied, the cylinder pressure as an intensive property in an engine responds at first, and in sequent engine speed, and turbine inlet temperature are responded in turn.

Fig. 7 shows the effects of air injection on the recovery time of engine speed. When compared with the response performance due to the air injection, it is clear that the case of air injection with 3 bars of pressure is quite improved. The difference of recovery time between the case of air injection pressure of 3 bar and without injection of air is gradually increased with the increase of rapid accelerating rate.

### *3.3. Effect of air injection on the change of accelerating time and response performance*

Fig. 8 shows the comparison of turbine inlet pressure with the acceleration rate of 20% for 1 second and 2 seconds at the experimental conditions of 1000 rpm and 163 Nm of engine load. In the case of supplying air with the 3 bars of injection pressure, it is obvious that air effects on the turbine inlet pressure appear a greater recovery response when acceleration is applied to the engine for 2 second than that for 1second. As can be seen in Fig. 8, the longer accelerated time results in the improvement for the response performance and fast recovery of turbine inlet condition.

Fig. 9 shows the effects of air injection period on the pressure of turbine inlet and compressor exit. As illustrated in figure, in the case of air injection for 1 second the pressure of compressor exit is reached to the steady state after about 5 seconds, but in the case of air injection for 3 seconds it is recovered more quickly about 2 seconds than that of for 1 second. In the case of air injection for 10 seconds the recovery time to the steady state is similar to the case of air injection for 3 seconds, but the pressure rises more largely. On the other hand, the pressure of turbine inlet is reached to the final steady state pressure in proportion to the increase of the period of air injection. But early stage of the turbine inlet

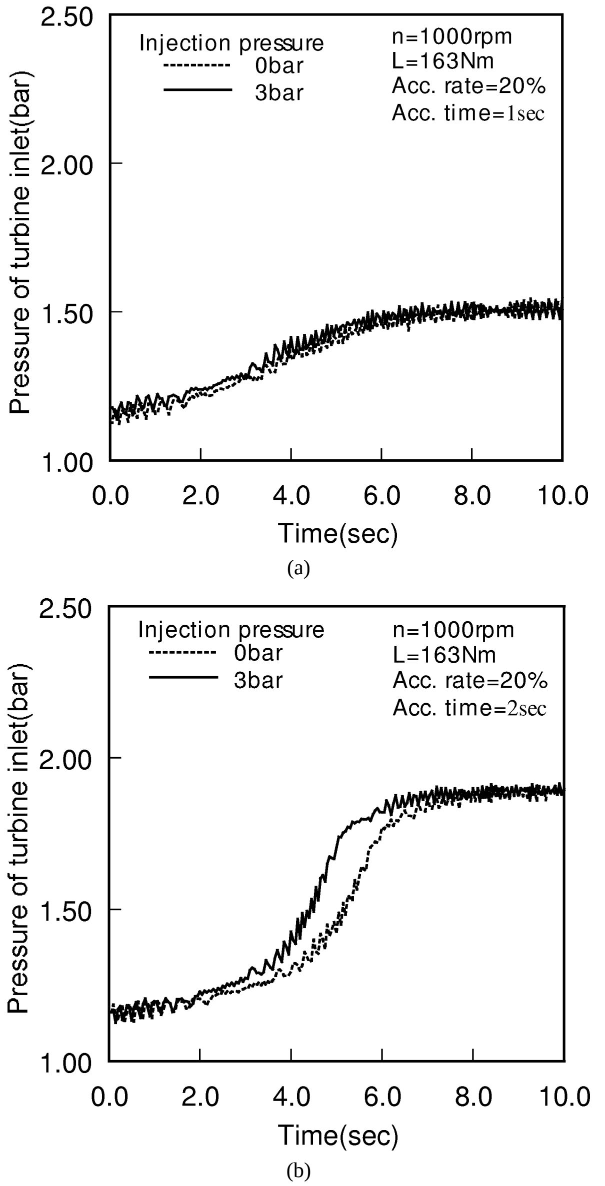


Fig. 8. Effects of injection pressure on the response performance of turbine inlet pressure: (a) Acc.time = 1 sec; (b) Acc.time = 2 sec.

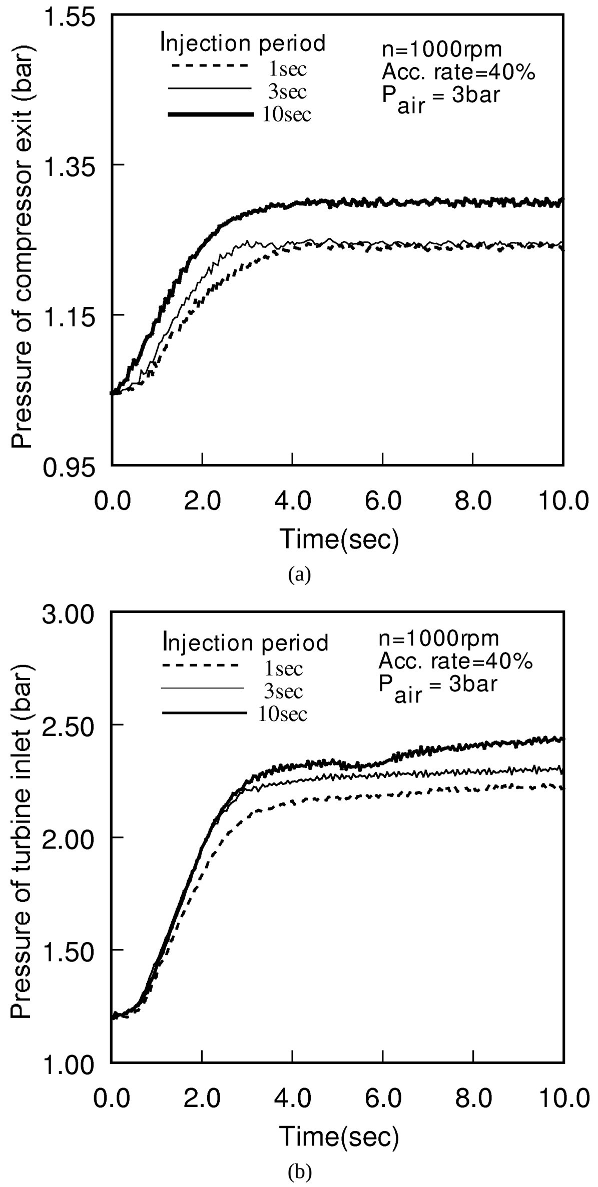


Fig. 9. Effects of injection period on the pressure of compressor exit and turbine inlet: (a) Compressor exit; (b) Turbine inlet.

and compressor exit shows that the initial response makes little difference.

### *3.4. Effect of air injection on the pressure variation of turbocharger and gas pressure*

Figs. 10 and 11 show the pressure history of turbine inlet, compressor exit and gas pressure of No. 1 cylinder at three kinds of air injection pressure and engine speed of 1000 and 2000 rpm. In the case of 1000 rpm of engine speed, both the turbine inlet and compressor exit pressure increase with an increase of air injection pressure. This indicates that higher injection pressure of air increases the gas pressure in cylinder and turbocharger performance parameters such as turbine inlet pressure and compressor exit pressure. Fig. 11 shows the effect of air injection on the performance parameters of turbocharger and cylinder pressure. In the case of 2000 rpm of engine speed with 3 bars of air-injection pressure, the intensive parameters of turbocharger are not changed because of sufficient supercharging by the fully operation of turbocharger.

As shown in Fig. 11, the pressure distribution during the valve overlap period indicates the best distribution with 2 bars of injection pressure at 2000 rpm of engine speed. This trend shows that the effect of air injection into the pipe of compressor exit brings about the better improvement of the pressure rise in the intake and exhaust systems at 1000 rpm of low speed than that at 2000 rpm of medium speed.

When the fast change of fuel-pump rack from 0 to 20% for 1 second is applied to the engine at 1000 rpm with

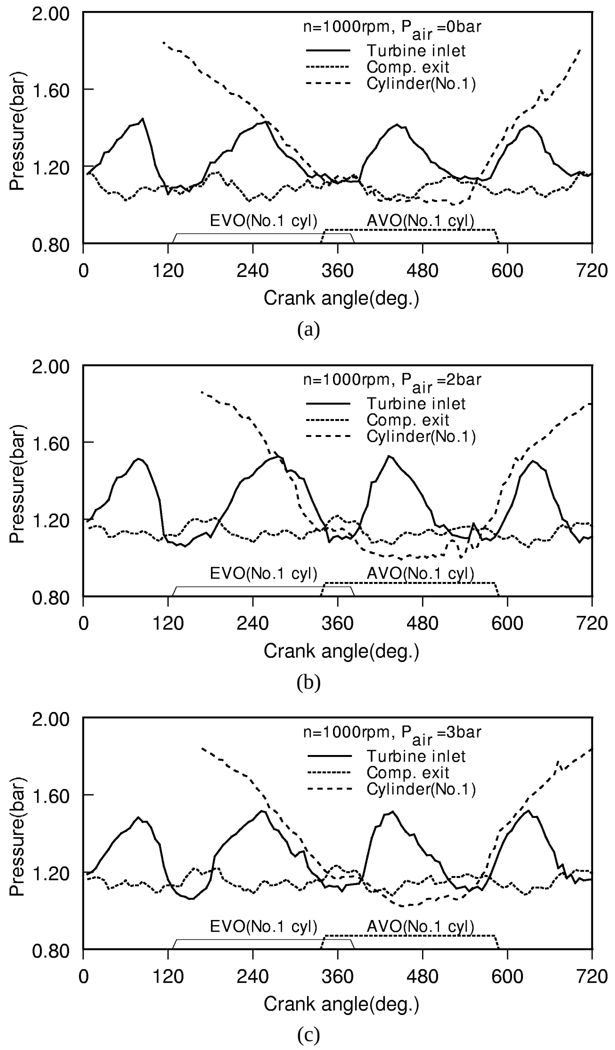


Fig. 10. Effects of injection air on the gas exchange process under full load at 1000 rpm: (a) no injection; (b) with 2 bar; (c) with 3 bar.

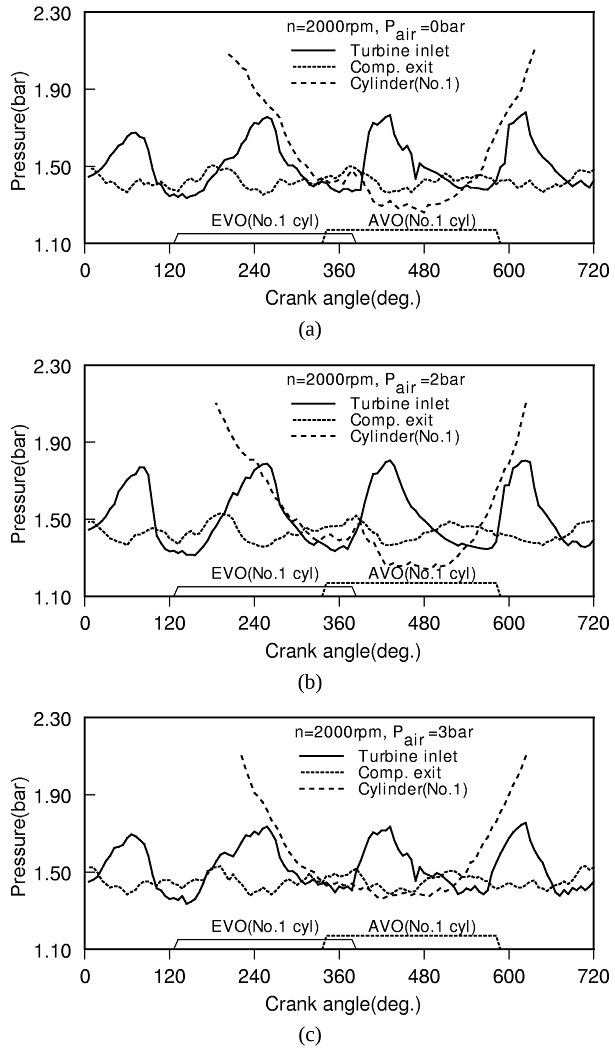


Fig. 11. Effects of injection air on the gas exchange process under full load at 2000 rpm: (a) no injection; (b) with 2 bar; (c) with 3 bar.

the load of 163 Nm, the comparison of cylinder pressure-crank angle diagrams due to the progress of engine cycles with air injection and without air injection are shown in Fig. 12. In the cylinder pressure-crank angle diagrams, the solid line is the air injection with 3 bars of injection pressure and the dotted line is the no injection of air. As shown in the results of mean effective pressure of the theoretical and experimental investigation by Bozza et al. [13], the cylinder pressures increase in accordance with the increase of the thermodynamic engine cycles. During the beginning period of transient, the low cycle occurs the low cylinder pressure because the turbocharger is commencing the operating. At the same cycles the gas pressures in the engine with air injection is greater than that of no injection of the air. It is clear that air injection into the intake manifold during the rapid acceleration period improve greatly the combustion performances of a turbocharged diesel engine.

## 4. Conclusions

An experimental study of the transient response characteristics has performed to investigate the effect of air injection into the intake manifold at compressor exit on the transient performance of the turbocharged diesel engine. Based on the results obtained throughout this study, the following conclusions are summarized.

(1) When the engine is rapidly accelerated in the load condition, the recovery time of turbine inlet pressure is a very longer than that of the condition without the load. An increase in the accelerating time shows the increase of the turbine inlet pressure and the shortening of transient duration.
(2) As the rate of a rapid acceleration for the engine further increased, the transient performance factors of test engine begin the response lately and require a long time to reach to their steady state conditions.

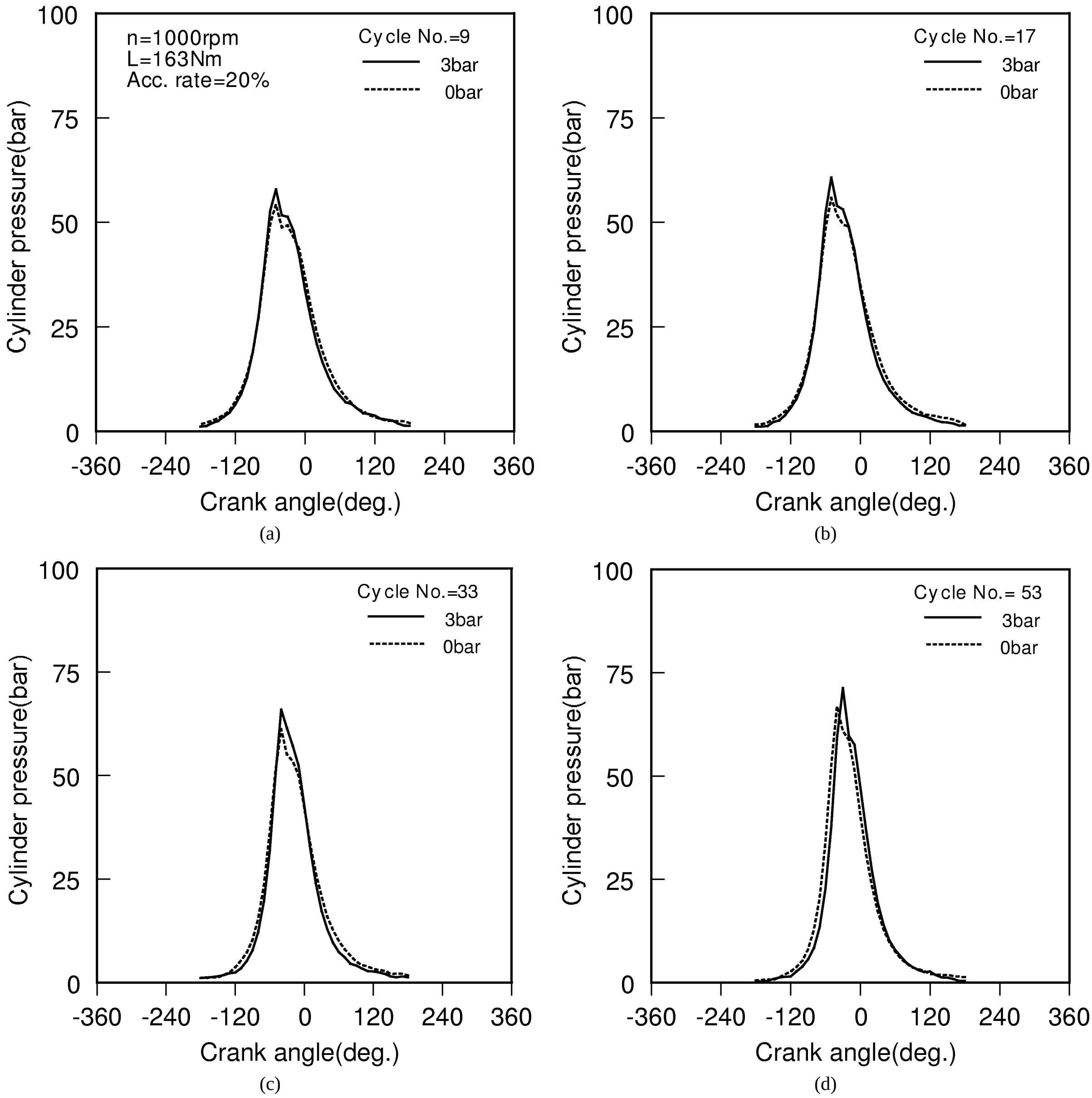


Fig. 12. Effects of air injection on the cylinder pressures due to the progress of engine cycles: (a) cycle number = 9; (b) cycle number = 17; (c) cycle number = 33; (d) cycle number = 53.

(3) At low speed range of the engine, the effect of air injection into the intake manifold shows the improvement of pressure variation of turbocharger and combustion pressure during the period of gas exchange process.
(4) Effect of air injection on the gas pressure in the engine indicated that cylinder pressure increased in accordance with the increase of air injection pressure. Also, accelerating time of fuel-pump rack is the main cause of the turbocharger lag, which has largely influence on the transient response of the engine.

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