Influences of Atmospheric Temperature on Performances of a Turbocharged High-Speed Four-Cycle Diesel Engine

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Abstract

In the present paper, the authors present the experimental results about the influences of atmospheric temperature on the performances of a small pre-combustion chamber type four-cycle diesel engine with a turbocharger for an automobile, and compare the influences with those of an un-turbocharged diesel engine. Furthermore, they correct the engine output at various atmospheric temperatures and investigate the necessity to vary the fuel injection timing when atmospheric temperature changes.

According to the results of experimental investigation as well as theoretical calculation assumed the turbine operating as a steady-flow type, it could be known that in the case of the rise in temperature the decrease in the output of the turbocharged engine was much more than that of the un-turbocharged engine. If we put on the ratio of engine outputs $p_i/p_{io}=(T_o/T)^n$, the exponent n was 3/4 in the un-turbocharged engine, and was about 0.88 in the turbocharged engine. However, the variation of injection timing had little influence on the performances of both engines.

1. Introduction

About 50 years ago, Dr. Büchi in Switzerland recognized the potential of turbocharging and introduced it successfully on ship, locomotive and aircraft engines. The further development of the turbocharger led to the development of gas turbines. In recent years, turbocharging has been introduced to automotive diesel engines. Also in our country, some commercial cars installing a turbocharger to increase the output per unit stroke-volume or per unit weight of the engine have been manufactured in a few diesel engine makers.

In the present paper, the authors discuss on the influences of atmospheric temperature on the performances of an automotive diesel engine installing a small size turbocharger, and compare the influences with those of an un-turbocharged engine. Furthermore, we try how to correct the outputs of un-turbocharged and turbocharged engines when the ambient temperature changes, and to estimate theoretically the output of engine installing the turbine operating as a steady-flow type.

The effects of injection timing on the engine performances are also discussed at various atmospheric temperatures.

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2. Notations

a : Ratio of amount of short-circuited air to that of total air delivered
c_m : Mean piston speed, m/sec
c_p : Specific heat at constant pressure, kcal/kg
c_v : Specific heat at constant volume, kcal/kg
D : Diameter of impeller, m
F_p : Piston area, m^2
F_r : Relative flow area at valve-overlap, deg·m^2
F_n : Turbine nozzle area, m^2
G : Weight-flow rate, kg/sec
H_u : Lower heating value of fuel, kcal/kg
L_o : Amount of air theoretically required for combustion, kg/kg
m : Exponent for compression and expansion of gases in cylinder
n_t : Rotational speed of turbocharger, rpm
p : Pressure, ata
p_e : Brake mean effective pressure, kg/cm^2
p_i : Indicated mean effective pressure, kg/cm^2
R : Gas constant, kgm/kg °K
$S_r = \mu_{rm} F_r / F_p$
T : Temperature, °K
z : Number of cylinder
δ : Ratio of number of molecules before combustion to that after combustion
$\zeta = \mu_n F_n / z F_p$
ε : Compression ratio of engine
κ : Ratio of specific heats $= c_p / c_v$
η_{adi} : Internal adiabatic efficiency of turbocharger
η_g : Diagram factor
λ : Excess air ratio on relation to fresh air retained in cylinder
ρ : Explosion ratio
σ : Cut-off ratio
μ_n : Flow coefficient of turbine nozzle
μ_{rm} : Flow coefficient of valve
ψ_{lt} : $\sqrt{2g \frac{\kappa_l}{\kappa_l - 1} \left\{ \left(\frac{p_t}{p_l}\right)^{2/\kappa_l} - \left(\frac{p_t}{p_l}\right)^{\frac{(\kappa_l+1)}{\kappa_l}} \right\}}$
ψ_{to} : $\sqrt{2g \frac{\kappa_t}{\kappa_t - 1} \left\{ \left(\frac{p_o}{p_t}\right)^{2/\kappa_t} - \left(\frac{p_o}{p_t}\right)^{\frac{(\kappa_t+1)}{\kappa_t}} \right\}}$

Subscripts for p, T, c_p, c_v and κ

g : Condition of combustion gases
o : Ambient condition
l : Condition at turbocharger outlet
t : Condition at turbine inlet

3. Experimental apparatus and method

The diesel engine and the turbocharger used in the present experiments are as follows;

a. Test engine (KE–25)

Type: Four-cycle water-cooled diesel engine

Combustion chamber: Pre-combustion chamber type

Stroke-volume: 5812 cm^3 ($4 \times 115 \times 140$)

Compression ratio: 17.5

Maximum output: 145 PS/ 2000 *rpm* (turbocharged)

b. Turbocharger (R–1021)

Turbine: Radial flow turbine type

Blower: Centrifugal compressor type

Maximum pressure ratio: 2.0/55000 *rpm*

Permissible turbine inlet temperature: 650 °C

The test engine and the turbocharger were connected to operate as a blow-down type. Fig. 1 shows the schematic arrangement of the experimental apparatus. The exhaust smoke density was measured with Bosch-type smoke meter. The relation between an indicated value and an excess air ratio will be discussed later. A number of performance tests were carried out under a constant temperature from 20 °C to 80 °C at an entrance of engine or turbocharger, and under a constant *bmep* from 6 to 8 kg/cm^2 (un-turbocharged) and from 7 to 9.5 kg/cm^2 (turbocharged).

The output of the turbocharged engine was corrected by the use of *bmep* vs. fuel delivery curves, each maximum fuel delivery was limited by the exhaust temperature of 650 °C or by the smoke density of about 5 of Bosch index. To discuss how much the performances of the engine are improved by altering the injection timing when the ambient temperature changes noticeably, a series of performance tests was carried out at 1800 *rpm* of the engine speed by altering the injection timing by 2.4°

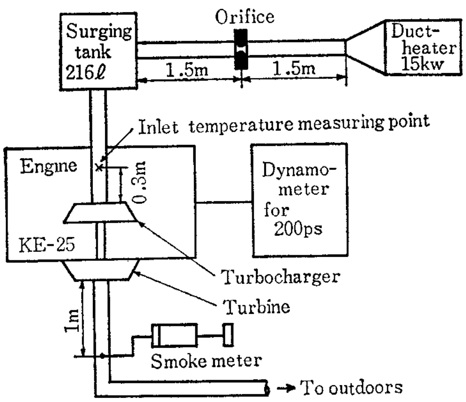

Fig. 1. Schematic arrangement of experimental apparatus.

crank angle, where the inlet temperatures of the engine and the turbocharger are 30 °C, 50 °C and 70 °C for the un-turbocharged engine, and 20 °C, 40 °C and 60 °C for the turbocharged engine.

4. Experimental results and considerations

In order to assure a smooth operation of a turbocharged engine in a wider range of atmospheric conditions, it is important to estimate exactly the engine output, and also it is very important to estimate the thermal loads of engine parts, due to an appreciable rise in the exhaust gas temperature caused by the reduction of excess air ratio. Therefore, the engine output running at vastly different condition of the atmosphere must be limited by the thermal loads of the engine and the turbine parts as well as the excess air ratio. That is, there are certain limits to the turbine inlet temperature and its speed.

In paragraph 4.1, the performances and the correcting factor of the engine output, when the turbocharger inlet temperature is altered, will be discussed on the basis of the decreasing ratios of the indicated and brake horse powers obtained for a constant fuel delivery or for a constant smoke density which would correspond to a constant excess air ratio.

As a rise of temperature at the end of compression stroke due to a rise of the turbine inlet temperature will shorten the ignition lag in the cylinder, engine performances will be improved by altering the injection timing. Thus, the authors discussed the engine performances on the basis of experimental data obtained at various timings, and also compared them with those of the un-turbocharged engine.

4.1 Theoretical consideration with respect to the influences of atmospheric temperature on the performances of a turbocharged diesel engine

There are close relations between the operating parameters such as boost pressure, turbocharger outlet temperature, turbine inlet temperature and pressure, excess air ratio, quantity of short-circuited air, engine speed, engine output and so on. At a certain operating condition, these parameters take certain values capable of maintaining an equilibrium-state. If we can solve the equilibrium-state equations containing these operating parameters as simultaneous equations, the value of each parameter at an equilibrium-state of the engine can be found[1]. Thus, we can estimate the engine performances from these values in the whole running range of the engine. For example, solving these simultaneous equations containing an independent variable T_o which is the turbocharger inlet temperature, we can discuss the influences of the ambient temperature on the engine performances.

For the turbocharged engine installing a turbine of a blow-down type, the cross-sectional area and the length of an exhaust pipe as well as the connection type of turbine and exhaust pipes are also important parameters. For avoiding troublesome calculations, however, it is reasonable to assume that the turbine operates as a steady-flow type, and that the ratio of short-circuited air flow to total air flow ($a=G_a/G_l$) is equal to zero due to short a valve-overlap duration.

For a stationary operation of the turbocharged engine, the following equations are established between operating parameters[1].

As the input of the compressor is equal to the output of the turbine, the turbine inlet temperature is geven by

$$T_t=\frac{\varphi_l^{\frac{\kappa_l-1}{\kappa_l}}-1}{1-\left(\frac{1}{c_{pt}}\right)^{\frac{\kappa_t-1}{\kappa_t}}}\cdot\frac{T_o}{\eta_T}\cdot\frac{\kappa_l}{\kappa_l-1}\cdot\frac{\kappa_t-1}{\kappa_t}\cdot\frac{\lambda L_o}{1+\lambda L_o-a}\cdot\frac{R_l}{R_t}\,. \quad (1)$$

The following relationship is established between boost pressure ratio and the compressor outlet temperature:

$$T_l=T_o\left\{1+\left(\varphi_l^{\frac{\kappa_l-1}{\kappa_l}}-1\right)\Big/\eta_{adl}\right\}. \quad (2)$$

The turbine inlet temperature is given by

$$T_t=\frac{T_l\left\{\frac{c_{vg}}{c_{pl}}\cdot\frac{\rho\sigma^m}{\delta}+\frac{c_{pg}}{c_{pl}}\cdot\frac{\kappa_g-1}{\kappa_g}\cdot\frac{1}{\delta}\cdot\frac{c_{pt}}{c_{pl}}+\frac{a\lambda L_o}{(1-a)(1+\lambda L_o)}\right\}}{\frac{c_{pg}}{c_{pl}}+\frac{a\lambda L_o}{(1-a)(1+\lambda L_o)}}\,. \quad (3)$$

Assuming the ratio of short-circuited air flow a is equal to zero,

$$T_t=\frac{T_l}{\delta\kappa_g}\left\{\rho\sigma^m+(\kappa_g-1)\cdot\frac{c_{pt}}{c_{pl}}\right\}. \quad (4)$$

The cut-off ratio σ is defined by the following equation:

$$\sigma=\frac{c_{vg}}{c_{pg}}\left(\frac{\eta_g}{c_{vg}}\cdot\frac{H_u}{1+\lambda L_o}\cdot\frac{\delta}{T_l\cdot\rho\varepsilon^{m-1}}+\frac{c_{pg}}{c_{vg}}-1+\frac{\delta}{\rho}\right), \quad (5)$$

where the ratio of number of molecules before combustion to that after combustion is expressed by

$$\delta=1+\frac{1.293(5.6H+0.8N)}{\lambda L_o}\,. \quad (6)$$

C, H and N are the weights of the atoms in the fuel of 1 kg which are assumed to be 0.858 kg, 0.126 kg and 0.015 kg, respectively.

As the gas weight through a turbine nozzle per one cycle is equal to the weights of the air charged and the fuel delivered per one cycle, the following equation will be established:

$$1+S_r\sqrt{R_lT_l}\,\frac{\psi_{lt}}{180c_m}=\frac{4\zeta}{c_m}\cdot\frac{R_lT_l}{\sqrt{R_tT_t}}\cdot\frac{c_{pt}}{c_{pl}}\cdot\frac{\lambda L_o}{1-a+\lambda L_o}\cdot\psi_{to}\,.$$

As $S_r\sqrt{R_lT_l}$ and a are equal to zero due to a very short valve-overlap duration, the turbine inlet temperature is given by

$$T_t=\left(\frac{4\zeta}{c_m}\right)^2\cdot\left(\frac{c_{pt}}{c_{pl}}\right)^2\cdot\left(\frac{\lambda L_o}{1+\lambda L_o}\right)^2\cdot\frac{R_l^2}{R_t}\cdot T_l^2\,. \qquad (7)$$

Constant values contained in the equations from 1 to 7 are:
$H_u=10000$ kcal/kg, $L_o=14.21$ kg/kg, $p_o=1.033$ ata, $\varepsilon=17.5$, $\rho=1.3$, $\eta_{adl}=0.7$, $a=0$ ($S_r=0$), $\eta_T=0.5$ and $m=1.3$.

4.2 Correction of engine output when atmospheric temperature changes

In recent years, it is by no means rare that many large-size diesel engines for bus, truck and for use in civil engineering and construction industry are frequently used in a wide range of atmospheric conditions. Thus, it is positively necessary for us to known how much the performances of the turbocharged engine are affected by atmospheric conditions. As a first step for this purpose, the influence of the inlet temperature on the engine output will be discussed in the following.

In general, the output of the turbocharged engine is restricted by three factors of exhaust smoke density, turbine inlet temperature and turbocharger speed. Fig. 2 shows how much the *bmep* and the exhaust smoke density are affected by the fuel delivery per one cycle (mg/cycle=2×mg/stroke), and by the turbocharger inlet temperature. From contour curves of the exhaust smoke density (*Sd*) and the

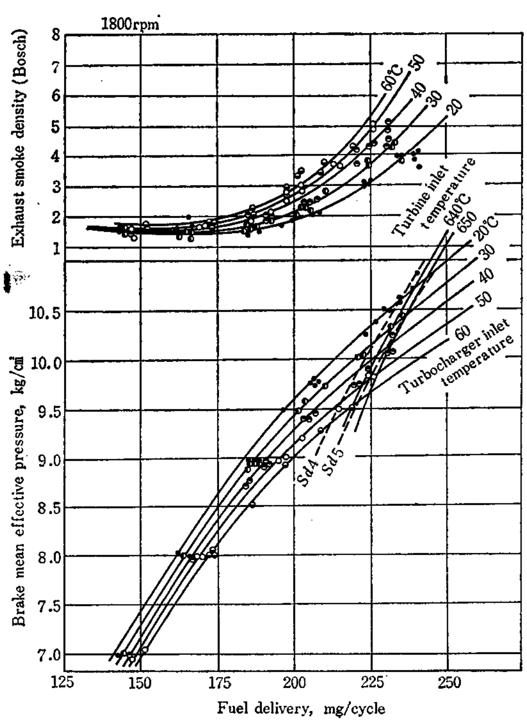

Fig. 2. Influences of ambient temperature on engine output and exhaust smoke (turbocharged).

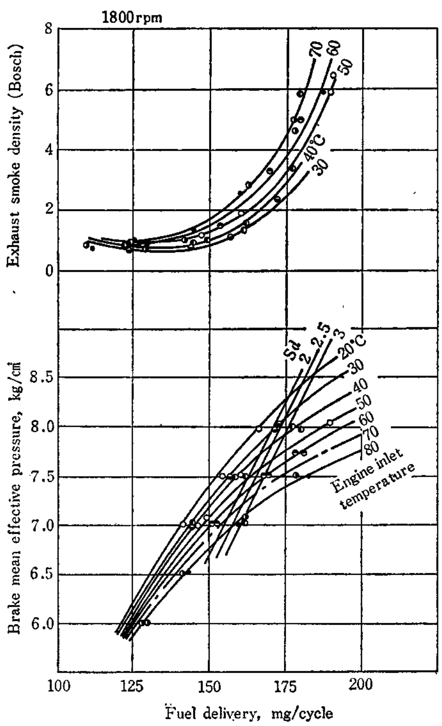

Fig. 3. Influences of ambient temperature on engine output and exhaust smoke (un-turbocharged).

turbine inlet temperature (t_t) filled in this figure, we can find two kinds of limits of the engine output and of the maximum fuel delivery for a normally aspirated engine.

Correcting the output of the engine on the basis of these curves, the decreasing ratio curves of output as shown in Figs. 6 and 7 can be obtained, where an indicated horse power is calculated roughly from values of brake horse power and friction loss obtained by Willan method on a normally aspirated engine.

The thermal efficiency of a diesel engine is usually affected by the utilization of air in cylinder. The more utilized the air, the more the efficiency is affected. Thus, the decreasing ratio of the engine output under a fixed fuel delivery may be increase with a decrease of the excess air ratio. That is, a formula for correcting the engine output at various atmospheric temperatures can not be expressed by a single form. To except the influence of air utilization, it is more effective to correct the engine output under a constant excess air ratio. The decreasing ratios obtained by such a method are shown in Figs. 4 to 6. It is reasonable to assume that a constant excess air ratio corresponds to a constant exhaust smoke density.

Figure 7 shows a belt-shaped curve of the excess air ratio (λ) vs. the exhaust smoke

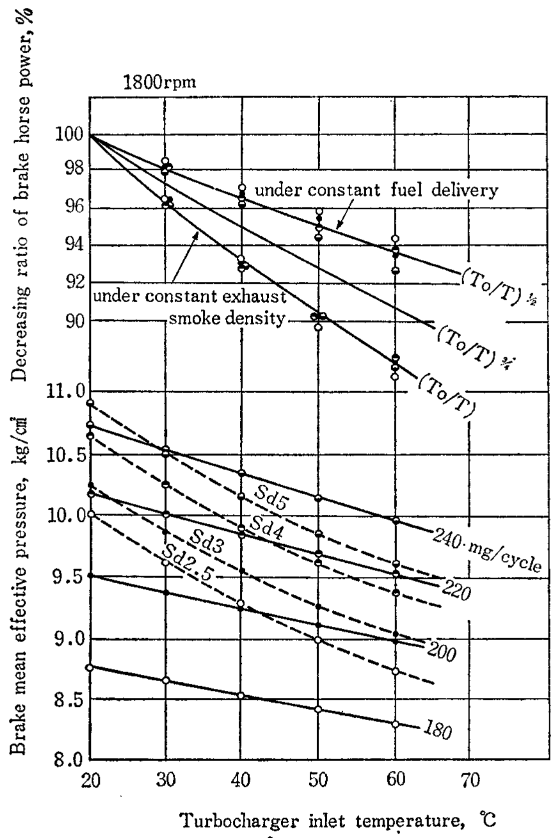

Fig. 4. Influence of ambient temperature on engine output under constant values of fuel delivery and exhaust smoke density (turbocharged).

density (*Sd*) measured with Bosch smoke meter. The data plotted in this figure are obtained in load performance tests at 20 °C to 60 °C of the turbocharger inlet temperature, and are marked with different marks for engine *rpm* tested. Referring to this figure, the situation of each plotted points is little affected by the engine speed, that is, by the boost pressure. This may be because of a little short-circuited air flow owing to a short valve overlap. Drawing curves of a constant *Sd* on a plane of *bmep* vs. fuel delivery, a correcting value of the brake horse power can be obtained at any turbocharger inlet temperature as shown in Figs. 4 and 5, where two standard temperatures for the correction are used, namely, 20 °C for the normally aspirated engine and 30 °C for the turbocharged engine. After correcting the brake horse power at an inlet temperature, it can be found that both outputs of un-turbocharged and turbocharged engines decrease nearly in proportion to $(T_o/T)^n$, and that the decrease in the output of the turbocharged engine is more severely affected by the temperature. However, it seems that the decreasing ratios of both engines are little affected by *Sd*.

The output of the diesel engine at a certain ambient temperature is usually corrected on the basis of indicated horse power. Fig. 6 shows the decreasing ratios

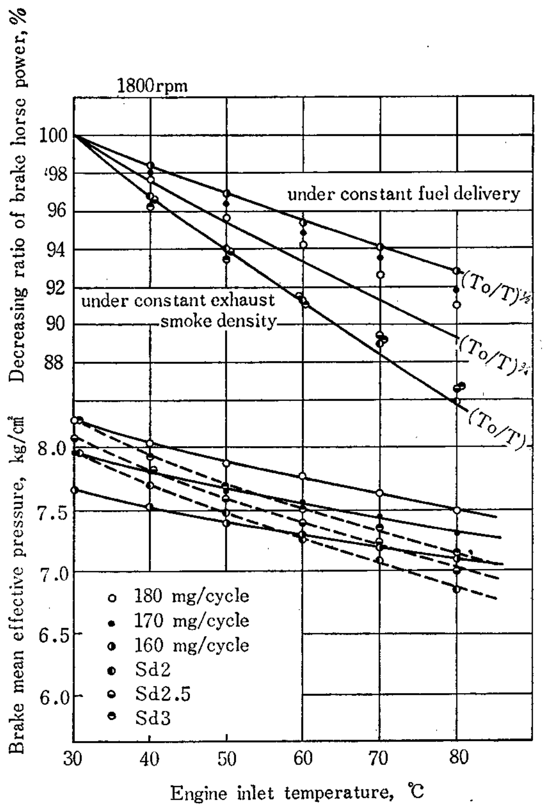

Fig. 5. Influence of ambient temperature on engine output under constant values of fuel delivery and exhaust smoke density (un-turbocharged).

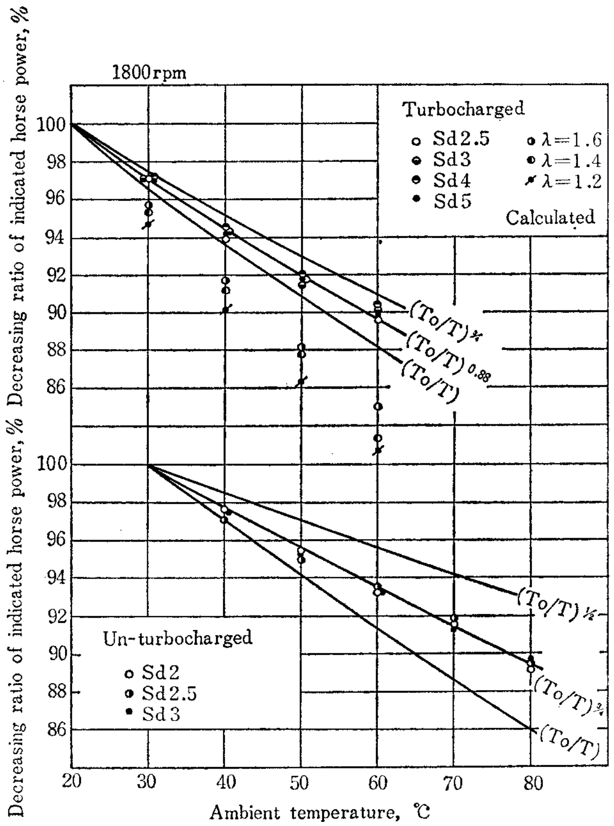

Fig. 6. Decreasing ratios and correction factors of indicated horse power for un-turbocharged and turbocharged diesel engine.

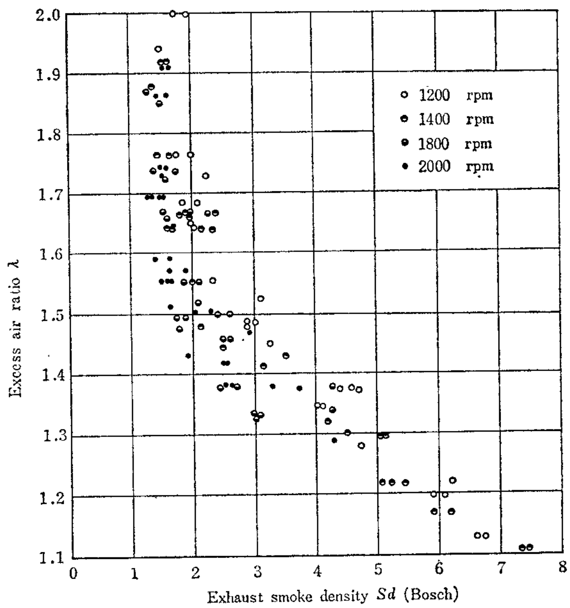

Fig. 7. Belt-shaped relation between exhaust smoke density and excess air ratio.

of the indicated horse power. The upper figure is of the turbocharged engine, and the lower figure is of the un-turbocharged engine. Referring to this figure, the output of the turbocharged engine decreases in propotion to $(T_o/T)^{0.88}$, even if the correcting factor is a little affected by the value of *Sd*. On the other hand, the output of the un-turbocharged engine decreases in propotion to $(T_o/T)^{3/4}$ as provided in the DIN and the CIMAC Standards. It seems that the output of the turbocharged engine is more affected by the ambient temperature and the excess air ratio used than that of the un-turbocharged engine. The points marked with ◐, ◑ and ⊘ in Fig. 6 were obtained by theoretical calculation. Referring to Fig. 6, the decreasing ratios of the indicated horse power of the turbocharged engine estimated at a constant excess air ratio are fairly larger than that obtained by the experiments. A main reason for this fact is that the connection of the engine and the turbine in theoretical calculation are of stdeay-flow type, though the connection in the experiment are of blow-down type in which the blow-down energy of the exhaust gas can be utilized.

The correction of the engine output at an atmospheric temperature T can be formulated as $p_i/p_{io}=(T_o/T)^n$, where p_{io} is a standard indicated horse power at 20°C, and p_i is an indicated horse power at T. Exponent n in the above formula may be affected by excess air ratio, engine speed, nozzle area of turbine, inner adiabatic efficiency of turbocharger and so on. For example, the exponent n becomes larger with a decrease in excess air ratio and nozzle area of turbine. That is, the engine output in these conditions is severely affected by the atmospheric temperature. Assuming the short-circuited air flow to be not equal to zero ($a\neq 0$), the boost pressure calculated becomes lower.

In the case of $G_{sp}\leqq zV_c/v_l$, p_i is given by

$$p_i=14.6\cdot\frac{H_u\eta_{th}\eta_g}{\lambda L_o}\cdot\left(1+\frac{S_r\sqrt{R_lT_l}\cdot\psi_{lt}}{180c_m}\right)\cdot\frac{p_l}{T_l}+p_l-p_t \qquad \text{kg/cm}^2. \tag{8}$$

Therefore, p_i is less affected by a, because the term $\dfrac{S_r\sqrt{R_lT_l}}{180\ c_m}$ increases with an increase of a.

On the other hand, in the case of $G_{sp}>zV_c/v_l$,

$$p_i=14.6\cdot\frac{H_u\eta_{th}\eta_g}{\lambda L_o}\cdot\frac{\varepsilon}{\varepsilon-1}\cdot\frac{p_l}{T_l}+p_l-p_t \qquad \text{kg/cm}^2. \tag{9}$$

Therefore, p_i is more affected by a than that in above case of $G_{sp}\leqq zV_c/v_l$, which means that a decrease in p_l caused by an increase in a can not be complemented. It would appear from these facts that the correcting formula at various atmospheric temperatures can not be expressed by a simple formula of $(T_o/T)^n$ such as $(T_o/T)^{3/4}$ for the un-turbocharged engine, for the output of the turbocharged engine is affected by many parameters even if the excess air ratio is of constant value.

As mentioned above, it can be confirmed by the theoretical calculation as well as by the experimental investigation that the influence of the atmospheric temperature on the indicated horse power of turbocharged engine is more than that on the un-turbocharged engine. This is because the inlet air flow for the turbocharged engine at a temperature obviously decreases much more than that for the un-turbocharged engine. For example, the decreasing ratios of the inlet air flow for the turbocharged engine are shown in the forms of $\rho/\rho_o=(T_o/T)^{1.73\sim1.63}$ for an excess air ratio λ of 1.2, $\rho/\rho_o=(T_o/T)^{1.59\sim1.48}$ for λ of 1.6, whereas the decreasing ratio for the un-turbocharged engine is shown in a form of $\rho/\rho_o=(T_o/T)^{4/3}$ for any λ. However, it is confirmed that the correcting formulas of the brake horse power for both engines approximate to a form of $(T_o/T)^{1.0}$.

4.3 Effects of injection timing on performances of turbocharged diesel engine at various atmospheric temperatures

If the inlet temperature rises, the ignition timing of an otto engine is sometimes required to retard owing to the advance of the ignition-nucleus formation and to the acceleration of flame propagation, which is caused by a rise of the compression temperature. For the diesel engine, it is also naturally expected that the performances of an engine are improved by a retard of the injection timing owing to a reduction of the ignition lag. To pursure such a possibility, the performance tests of the un-turbocharged and the turbocharged engines were carried out by retarding the injection timing from $T2$ to $T6$ with a rate of 2.4° crank angle, and under a fixed

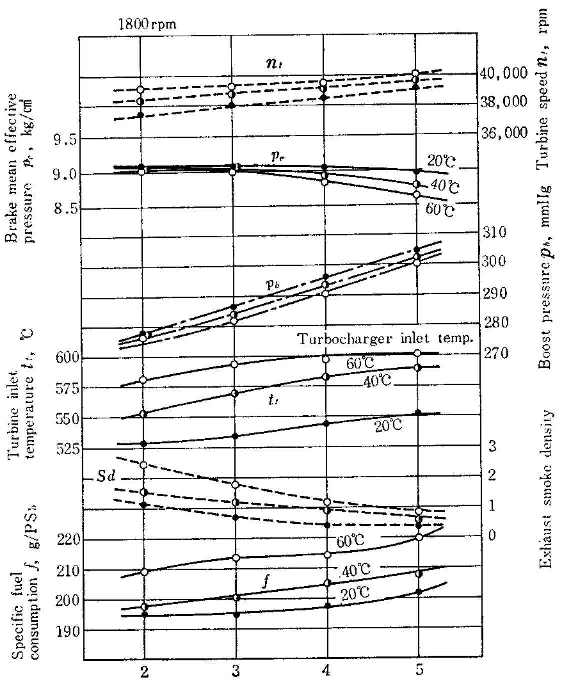

Fig. 8. Effects of fuel injection timing on various performances of turbocharged diesel engine.

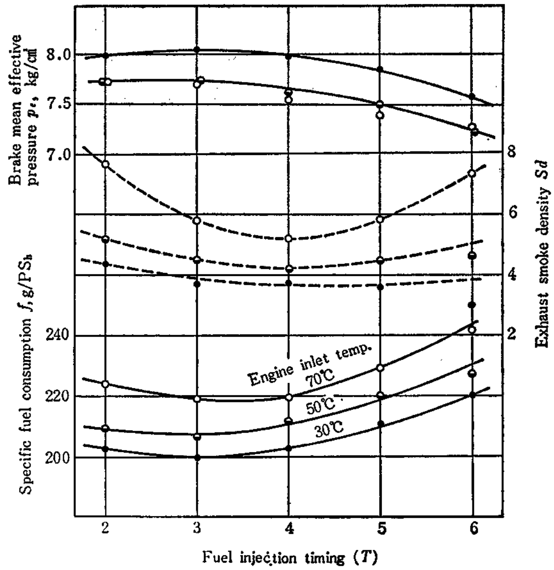

Fig. 9. Effects of fuel injection timing on various performances of un-turbocharged diesel engine.

fuel delivery at three inlet temperatures, where $T2$ corresponds to 20° BTDC.

Figures 8 and 9 show some examples of the results of these performance tests. The quantity of fuel delivery at an engine speed of 1800 *rpm* was fixed at a value which produces 9 kg/cm² of p_e for the turbocharged engine and at a value which produces 8 kg/cm² for the un-turbocharged engine. Referring to Fig. 8, it is evidently shown that the output of the turbocharged engine is not severely affected by retarding the injection timing, and that the values of p_e and f for any injection timing remain almost unchanged. This is because the decrease in *imep* resulting from a retard of the injection timing is, as is evident from Eqs. (8) and (9), supplemented by the rise of the boost pressure p_l owing to an increase of the turbine output. As the optimum injection timing for the turbocharged engine extends practically over a range of about 5° crank angle, the engine output at a higher inlet temperature can not be supplemented by retarding the timing slightly. From a viewpoint of protecting turbine blades, it is better to advance the timing than to retard.

In the case of the un-turbocharged engine, there are two kinds of the optimum injection timings for a fuel consumption and for an exhaust smoke density. Judging from the fact that there is a little difference of the optimum timings at 30°C and 70°C for the fuel consumption, however, it might as well be said that it is hardly necessary to vary the timing, even if the inlet temperature changes considerably.

4.4 Non-dimensional expression of turbine performances

It is very convenient to use the non-dimensional expression for representing the performance of the turbine or the compressor operating under various conditions. Applying the expression to a representation of the performance of the

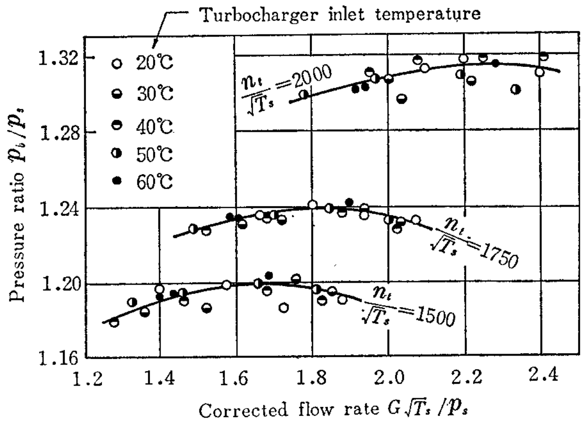

Fig. 10. Non-dimensional expression of turbine performances.

turbocharger[2)], p_b/p_s is expressed by a form of

$$p_b/p_s=f\left(\frac{n_tD}{\sqrt{T_s}},\ \frac{G\sqrt{T_s}}{D^2p_s}\right).$$

The impeller diameter D of the turbocharger used in our test is constant, so that the following expression can be obtained.

$$p_b/p_s=f\left(\frac{n_t}{\sqrt{T_s}},\ \frac{G\sqrt{T_s}}{p_s}\right),$$

where the subscripts of s and b for p and T signify the inlet and the outlet conditions of the turbocharger, respectively.

The results of performance tests at various inlet temperatures are illustrated by constant $n_t/\sqrt{T_s}$ curves in Fig. 10. Referring to this figure, it can be found that running points of the turbocharger at various inlet temperatures do not deviate so much from a constant $n_t/\sqrt{T_s}$ curve.

5. Summary

The results of the present investigation as to the influences of the atmospheric temperature on the performances of the turbocharged diesel engine are summarized as follows:

(1) In the case of delivering a fixed amount of the fuel into the turbocharged diesel engine, the rise in the turbocharger inlet temperature results in the fall of the excess air ratio as well as the rise of the turbine inlet temperature. However, unless the engine load is higher than a *bmep* of 9.5 kg/cm^2, the turbine will never increase its speed owing to the reduction of the weight-flow rate of the exhaust gas. From these facts, the maximum fuel delivery of the turbocharged diesel engine may be limited by the permissible inlet temperature of the turbine if used at a higher atmospheric temperature.

(2) Evaluating the influence of the atmospheric temperature on the output of the turbocharged diesel engine running at a constant excess air ratio, it became evident from experimental investigations as well as theoretical calculations that the output of the turbocharged diesel engine was more affected than that of the un-turbocharged diesel engine.

(3) Correcting the engine output at various atmospheric temperatures, the ratio p_i/p_{io} for the un-turbocharged diesel engine could be expressed to be proportional to $(T_o/T)^{3/4}$. For the turbocharged diesel engine, it could be known after repeating many experiments that the ratio p_i/p_{io} was expressed to be proportional to $(T_o/T)^{0.88}$, the exponent of 0.88 is a little larger than the exponent of 3/4, and is slightly affected by turbine nozzle area, engine speed and so on. In the case of correcting the brake horse power with a constant value of the excess air ratio, p_e/p_{eo} of both engines are expressed to be proportional to $(T_o/T)^{1.0}$.

(4) Comparing the correction of the engine outputs between the results of the experiment and of the theoretical calculation based on the assumption that the turbine is operating as a steady-flow type, the ratio p_e/p_{eo} calculated with a constant value of the excess air ratio is propotional to $(T_o/T)^{1.4}$. From this fact, it seems that the output of the engine installing a steady-flow type turbine is severely affected by the atmospheric temperature because of no utilization of the pulse energy in the exhaust pipe.

(5) Though the effect of the injection timing on performances of the pre-combustion chamber diesel engine is less than that of the open chamber diesel engine, we cannot conscientiously say that the optimum injection timing does not exist. As the optimum injection timing for the turbocharged diesel engine kept almost constant in a wider range of the crank angle, we succeed badly in an attempt to recover the decrease in the engine output caused by the rise of the atmospheric temperature.

(6) The results of many performance tests proved clearly that we could apply the non-dimensional expression to represent the turbine performances at various atmospheric temperatures.

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