Development of an algorithm code concept to match the diesel engine and turbocharger

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Abstract. Not all turbochargers can utilize exhaust gases from diesel engines. The turbocharger must match with the diesel engine. Two methods for match between turbocharger and diesel engine are developed by Patil and Stones. The purpose of this research is to develop algorithm code that describe a matching concept between the turbocharger and diesel engine based on the steps taken by Patil and Stones. The algorithm has to decide whether one turbocharger match the engine with using engine specification data and turbocharger performance maps as input. One keyword to match is the mass flow rate, this parameter become consideration whether turbocharger match with diesel engine. The results show that the Patil code concept (algorithm) can make limitation area for the turbocharger, but after entering the performance map of turbocharger, it turned out that the turbocharger criteria entered were in the same place and outside the criteria. The result of Stones concept is the turbocharger performance map can cover the operation engine area.

1. Introduction
The Indonesian Central Statistics Agency (BPS) presents data on the use of motor vehicles in Indonesia in 2016 reaching 129,281,079 units. This is not small number whose enormous potential especially in pollution. Then if we look at the growth data, from 2014 to 2015 the addition of the number of motor vehicles reached 7,184,925 units and growth from 2015 to 2016 reached 7,886,894 units [1]. The growth rate will continue to rise along with the high number of population which causes an increase in demand for transportation.

If we look at the international world today, they are starting to slowly substitute vehicles from vehicles based on internal combustion engines to electrical engines. One article from The Economist by Jon Berkeley said that the current era of combustion engines will die due to the development of electric cars [2]. This electrical development has been going on for a long time and this development was carried out not only on the vehicle itself but on the supporting infrastructure of the electric vehicle itself. This transformation is not unreasonable, because it sees the reality of the environment and the depletion of fossil fuel availability which is certainly not in line with the increasing demand for energy.

The reality that exists in Indonesia with vehicle users based on Internal Combustion is high and the trends that exist in the international world, it is time for Indonesia to make changes to adjust to the international world. Changes are of course done gradually. The number of hundreds of millions with large growth is not an easy thing to change drastically but is not a difficult thing to do in stages. One solution that can be used to bridge it is to develop products that are supporting the existing internal
combustion engine. A reliable tool to answer these challenges, one of which is a turbocharger. The effect of turbocharging system can improve performance of engine and decrease specific fuel consumption [3]. Turbochargers whose principle is to convert the kinetic energy of the exhaust gas is converted into compression energy in the incoming air. The amount of incoming air pressure causes the increase in the density of the incoming air. Increasing the price of density in the same space will cause an increase in the amount of air entering the engine cylinder so that power increases, volumetric efficiency increases and has an important role in terms of specific fuel consumption and pollution emissions [4,5]. Then Tancrez and Serrano also said, that each turbocharger needs to be matched to achieve the desired performance in every different operating condition [6,7].

2. Method

The software development method for matching turbochargers uses an algorithm performed by Patil and compared to the method carried out by Stones [8,9]. In general, the steps taken by Patil are to make the operating area based on the mass flow rate and match the turbocharger criteria to the engine characteristics. The following steps are made by Patil to match turbocharger and diesel engine.

The mass flow rate equation is made under normal load conditions and maximum torque. This mass flow rate equation is a function of the pressure and temperature of the air entering the diesel engine intake manifold.

\[ m_A = \frac{\eta_{vol} \times D \times N \times p}{2 \times R \times T} \]  

(1)

where

- \( m_A \): mass flow (kg/s)
- \( D \): displacement per cycle (m³)
- \( N \): engine speed (rotations/seconds)
- \( P \): intake manifold pressure (Pa)
- \( R \): air gas flow constant (J/kg.K)
- \( T \): intake manifold temperature (K)

Equation (1) is made in two conditions as a turbocharger operating limit. The first condition is the engine operating condition and the second is the maximum condition when the engine produces maximum torque. The engine used is 1KD-FTV 3.0 D-4D. The engine has 2982 cc displacement and the magnitude of \( R \) is 287.05 Joules / kg.K. The volumetric efficiency value (\( \eta_{vol} \)) is a function of engine speed. This engine operates normally at 2400 rpm and maximum torque is reached at 4000 rpm. Here are the volumetric efficiency values used at each engine speed.

| Engine Speed (rpm) | \( \eta_{vol} \) | \( p_{AID} \) (mbar) | \( p_{int} \) (mbar) | \( T_m \) (°C) |
|-------------------|-----------------|---------------------|---------------------|----------------|
| 2400              | 90%             | 7                   | 120                 | 36             |
| 4000              | 75%             | 20                  | 140                 | 48             |

Then the pressure and temperature entering the intake manifold are evaluated by calculating the decrease in depression in the intake manifold (\( p_{AID} \)) and in the intercooler (\( p_{int} \)). This pressure drop is a function of engine speed. This is explained in table 1. The value is taken from Patil adjusted to the rated operating conditions and maximum torque operation. Then the temperature when entering the intake manifold depends on engine speed. The boundary conditions are then entered into equation (1) to produce two equations for the two conditions, e.g. equation (2) for rated operation and equation (3) for maximum torque operation.

\[ m_A = (1.87 \times 10^{-4}) \frac{P}{T} \]  

(2)
The linear equation produced by equations (2) and (3) are plotted in a Cartesian diagram, where the x-axis is the flow parameter and the y-axis is the ratio of the compression. Flow parameters are defined by equation (4).

\[ FP = m_A \frac{T_{\text{ref}}}{T_{\text{int.c}}} \]  

(4)

The value of \( T_{\text{ref}} \) is 298 K which is the standard temperature. Then \( T_{\text{int.c}} \) is the temperature going out from the intercooler to the intake manifold. The boundary of the area formed by the two lines by equations (2) and (3) is used as an evaluation area for the turbocharger to enter the engine operating area.

In addition to the engine operating area, evaluations used are the required engine density (ED), actual volumetric flow (\( V_a \)), mass flow rate (\( M_{\text{air}} \)), and fuel flow rate (\( M_{\text{fuel}} \)) defined in equation (5), (6), (7) and (8) respectively.

\[ ED = \frac{V_a}{\eta_{\text{vol}} \times D \times N} \]  

(5)

where

- \( V_a \): Actual Volumetric Flow (m\(^3\)/s)
- \( D \): Displacement of engine (m\(^3\))
- \( N \): Engine speed (rad/s)

\[ V_a = \frac{M_{\text{air}} \times T}{D_a \times P} \]  

(6)

where

- \( T \): Temperature ratio of \( T_{\text{int.c}}/288 \) K
- \( P \): Pressure ratio of \( P_{\text{int.c}}/1.013 \) bar
- \( D_a \): Standard air density at temperature 288 K and pressure 1.013 bar
- \( M_{\text{air}} \): air mass flow (kg/s)

\[ M_{\text{air}} = M_{\text{fuel}} \times AFR \]  

(7)

where

- \( M_{\text{fuel}} \): Fuel flow (kg/s)
- \( AFR \): air fuel ratio (mass based)

\[ M_{\text{fuel}} = EP \times BSFC \]  

(8)

where

- \( EP \): Engine Power (kW)
- \( BSFC \): Brake Specific Fuel Consumption (g/kWh)

Engine and BSFC power data are obtained from the dyno test, where both quantities change depending on engine speed. Power and torque against engine speed are data that can be taken from dyno test. Then to get BSFC from dynotest data, the steps taken by using equation (9) to get the BSFC are started by using equation (10) to get the fuel flow rate (\( m_f \)). Equations (9) and (10) are obtained from Arismunandar in Ginting [10].

\[ BSFC = \frac{m_f}{EP} \]  

(9)

\[ m_f = \frac{m_f \times N \times s}{n} \]  

(10)

where

- \( m_f \): mass of fuel
- \( N \): engine speed (rotation/second)
The mass of the fuel is determined based on calculations made by referring to the book Arismunandar which states that the use of specific fuels for diesel engines ranges from 0.140 – 0.180 kg / (PS. hours) equals to 190-245 g/kWh [11]. Based on these data, the price value of mf is 50 grams.

The value of density required to enter the engine (ED) then becomes the handle of the suitability of the engine and turbocharger. Turbocharger itself is evaluated based on the value of its mass flow rate which further from the compressor performance map gives the price of compressor efficiency and pressure ratio. The value of the compression ratio and the subsequent efficiency is used to calculate the $T_{c2}$ value, which is the temperature at outlet of the intercooler. The relationship between compression ratio, compressor efficiency and $T_{c2}$ is explained in equation (11).

$$T_{c2} = T_{c1} + \frac{T_{c1}}{\eta_c} \times \left( \frac{\gamma - 1}{R_c \gamma} - 1 \right)$$  \hspace{1cm} (11)

where

- $T_{c1}$: inlet temperature of the compressor
- $T_{c2}$: outlet temperature of the compressor
- $\eta_c$: compressor efficiency
- $R_c$: compressor pressure ratio
- $\gamma$: ratio of specific heat = 1.4 for air

Then the value of $T_{c2}$ is entered to equation (12) to see whether the density entering the engine is the same as ED or not.

$$DR_c = \frac{T_{c1}}{T_{c2}} \times R_c \times PD$$  \hspace{1cm} (12)

where

- $DR_c$: requirement density (kg/m$^3$)
- PD: pressure drop across intercooler (PD=0.12)

The Patil’s matching method is then compared to the matching method performed by Stones based on the mass flow rate. The mass flow rate formula is stated in equation (13).

$$m_a = \rho_3 \times N^* \times V_s \times \eta_{vol}$$  \hspace{1cm} (13)

where

- $\rho_3$: density at intercooler turbocharger outlet (kg/m$^3$)
- $N^*$: number of rotations per second (1/s)
- $V_s$: swept volume (m$^3$)

The value of density that comes out of the intercooler ($\rho_3$) is obtained by the diagram in figure 1.

![Figure 1. Control volume diagram of turbocharger and intercooler.](image)
Equation (14) is used to get $p_3$ by using the ideal gas assumption.

\[
\frac{\rho_3}{\rho_1} = \frac{p_2}{p_1} \left[ 1 + (1 - \varepsilon) \left( \frac{p_2}{p_1} \right)^{(\gamma - 1)/\gamma} \right]^{-1}
\]

(14)

where

- $p_2/p_1$ : turbocharger compression ratio
- $\varepsilon$ : intercooler efficiency

The results of the mass flow rate are then varied based on the compression ratio then entered into the compressor performance map. If the operating area of the engine mass flow rate is inside the compressor performance map, the turbocharger can be used on the engine.

3. Results and discussion

The matching method used by Patil succeeded in making the operating area of the engine based on compression ratio and mass flow rate. The area is limited by rated engine speed and maximum torque. The area of operation is shown in Figure 2. The area is between line 2400 rpm and 4000 rpm, and called as the breathing line compressor. The interval of mass flow of breathing line at compression ratio 1.3 is $0.085 \leq x \leq 0.112$ kg/s which x is mass flow. The length of the interval is 0.0267 kg/s. The length of internal increases with the increase of compression ratio. As we can see, the length of interval at compression ratio 3.75 is 0.0699 kg/s. These result coherences with the work from Patil and Stones [8,9].

![Breathing Line Compressor](image.png)

Figure 2. Breathing line compressor using Patil’s method [4].

Then this area was tested by entering three types of turbochargers based on the compressor performance map. The types of turbo are G25-550, G25-660 and GT-3582R. We can see the operation point from the three turbocharger on figure 2. The two points are located outside the area (bounded by two breathing lines). The other two points coming from different turbochargers occupy the same position. The G25-550 turbocharger has interval operation for compression ratio 1.5 between around 0.056 kg/s and 0.3 kg/s which can cover the engine breath line [12]. This shows that method can be applied for matching chart process.
Patil’s approach method needs to be compared with other methods, e.g. Stones. Stones’s method is different from Patil’s, the Stones entering the engine operating area into the turbocharger compressor performance map. The turbocharger compressor we use is G25-550. The results of matching process from Stones is depict in figure 3 [12].

Figure 3. Breathing line compressor using Stones’s method in compressor map [4].

The dashed line is the operating area at rated operation and the solid line is operating at maximum torque. It appears that the two lines are inside the turbocharger operation area. Based on this matching diagram, the turbo G25-550 is matched with 1KD-FTV 3.0 D-4D engine. However, turbocharger has not been fully utilized because so many are not covered by the engine breathing line and the best efficiency of turbocharger is outside the engine breath line. The engine breath line only covers efficiency turbocharger from 68% to 75%. Selection of a better turbocharger to reach the highest efficiency is still possible because the matching process carried out by Tancrez reaches that point. Tancrez also make power constant line as consideration because upper limit of compressor map is maximum power [6].

These results are more theoretical studies that require experimental data to validate them. Future research is expected to carry out experiments by varying three turbochargers combined with two different diesel engines to ensure validation of the matching method.

Another thing that has to be concerned is compressor map. The left side boundary is surging area and these matching process can accommodate surging boundary, but the upper limit needs to be found because the area is limited by maximum power generated by the engine. Maximum power produced is related maximum operational temperature that affected to strength of material.

4. Conclusion
The method used by Patil to match the turbocharger and engine is not fully revealed because in the analysis cannot use specific criteria from turbocharger to breathing line compressor. The method used by Stones can answer matching process between the 1KD-FTV 3.0 D-4D engine and G25-550 turbocharger. Further development is needed in validating matching methods with experiments and expanding studies by providing an upper limit related to maximum power of the engine.
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