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Turbocharger selection and energy analysis of MGU-H for commercial vehicles

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ABSTRACT

This paper presents the Regenerative turbocharging which basically electrically assisted turbo is charging. This system aims to improvise two primary parameters of the turbocharger; namely performance and turbocharging. In this system, an electric motor coupled with a battery is added to the standard turbo setup, the motor is attached to the same shaft as the turbo impellers. When there is wastegate exhaust, the turbo rotates the motor, thus making it act like a generator which in turn charges the battery. This energy can later be used to rotate the motor, which will, in turn, boost the turbo, in situations of turbo lag, and low rpm, in the low end. The proposed system thus improves performance by eliminating turbo lag and also makes the engine energy efficient.

Keywords— *Turbo lag, Turbo boost, Electronics, Turbine, Isentropic efficiency*

1. INTRODUCTION TO MGU-H

A recent trend is about the best ways of using the deployable sources of energy into useful work in order to reduce the rate of consumption of fossil fuel as well as pollution. Out of all the available sources, the internal combustion engines are the major consumer of fossil fuel around the globe. The Internal Combustion Engine has been a primary power source for automobiles and automotive over the past century.

Out of the total heat supplied to the engine in the form of fuel, approximately, 30 to 40% is converted into useful mechanical work. The remaining heat is expelled to the environment through exhaust gases and engine cooling systems, resulting in entropy rise and serious environmental pollution, so it is required to utilized waste heat into useful work. The recovery and utilization of waste heat not only conserves fuel, usually fossil fuel but also reduces the amount of waste heat and greenhouse gases damped to the environment. It is imperative that serious and concrete effort should be launched for conserving this energy through exhaust heat recovery techniques. Such a waste heat recovery would ultimately reduce the overall energy requirement and also the impact on global warming.

The main targets in developing combustion engines actually are to improve transient behavior combined with high output, a wide rpm range with constantly high torque and a reduction of fuel consumption. To achieve these targets there is no way around an adequate turbocharging system. The major problem of all turbocharged combustion engines is their delayed response (turbo lag) regarding the mean effective pressure build-up at low rpm. With turbochargers, the charging process is only coupled to the internal combustion engine on the thermodynamic level. On the one hand, this offers the advantage that the exhaust gas energy can be utilized, on the other hand, the disadvantage that depending on the load point in the characteristic field, and the turbocharger speeds vary significantly.

In case of a load step taking place at low engine speeds (1500 to 2000 rpm), only a low enthalpy gradient is available to the turbine for the compressor capacity and power loss. This results in low available power to accelerate the turbocharger to the stationary endpoint. This incomplete charging process again does not only negatively influence the drivability but also energy consumption as well as the pollutant emissions. Even with modern turbocharged engines, a large portion of the gas escaping in the driving cycle is emitted during dynamic operating phases. [5]

1.1 MOTOR-GENERATOR UNIT (MGU) ASSISTED TURBOCHARGER

In normally aspirated piston engines, intake gases are "pushed" into the engine by atmospheric pressure filling the volumetric void caused by the downward stroke of the piston (which creates a low-pressure area), similar to drawing liquid using a syringe. The amount of air actually inspirited, compared to the theoretical amount if the engine could maintain atmospheric pressure, is called volumetric efficiency. The objective of a turbocharger is to improve an engine's volumetric efficiency by increasing the density of the intake charge.

The turbocharger's compressor draws in ambient air and compresses it before it enters into the intake manifold at increased pressure. This results in a greater mass of air entering the cylinders on each intake stroke. The power needed to spin the centrifugal compressor is derived from the kinetic energy of the engine's exhaust gases. In the MGU-H assisted turbocharger exhaust energy is converted to mechanical shaft power by an exhaust turbine. The mechanical power from the turbine is then used to drive the compressor, and also the MGU-H At its fastest point the turbocharger is rotating over 100,000 revolutions per minute or over 1,500 times per second, so the pressures and temperatures generated will be enormous. Some of the energy recovered from the exhaust will be passed on to the MGU-H and converted to electrical energy that will be stored in storage systems and can later be re-deployed to prevent the turbo lag too much under braking. The additional electrical energy could be used to power more advanced engine technologies, such as electromagnetic valve actuation, electric intake charge cooling and electric-powered super-charging or electrical exhaust after-treatment. The figure below shows the schematic layout of the proposed model of MGU-H assisted turbocharged engine in commercial vehicles. [5]

The main components of this engine include –
(a) Internal Combustion Engine (ICE)
(b) Turbine
(c) Compressor
(d) MGU-H
(e) Power and control electronics (ECU)
(f) Energy storage system

1.2 MOTOR GENERATOR UNIT FOR HEAT RECOVERY (MGU-H)

A motor-generator unit (MGU) is an electrical machine. When operating as a motor, the MGU converts electrical energy to mechanical energy. When it operates as a generator the MGU converts mechanical energy to electrical energy. A turbocharger uses an exhaust-driven turbine to drive a compressor to increase the density of the intake air consumed by the engine and so make more power for a given displacement. The residual heat energy contained in the exhaust gases after expansion in the cylinders of the engine is converted to mechanical shaft power by the exhaust turbine. The mechanical power from the turbine is used to drive the compressor, and also the MGU-H (H for Heat – exhaust energy recovery).

1.2.1 OPERATION MODES

(a) Discharging mode:

When the driver depresses the throttle, the MGU assisted turbocharger initially acts as an electric supercharger. The compressor motor-generator is powered from the energy storage medium allowing it to accelerate to full operating speed in the span of few milliseconds. This rate of acceleration eliminates the turbo lag which is a major limiting factor on the performance of standard turbocharged engines. During this transient stage, the engine control unit (ECU) on a standard turbocharged engine uses a combination of sensors such as lambda sensors and air mass flow sensors to regulate the fuel flow rate. In an MGU assisted equipped turbo-engine the ECU can deliver the precise fuel flow rate for complete combustion more accurately. This is achieved by directly controlling the airflow rate and boost pressure via control of the compressor speed. Under braking, the MGU-H converts to a motor to keep the rotational speed of the turbocharger high enough to avoid turbo lag, the curse of the turbo engine. Turbo lag is a phenomenon experienced under braking when the turbocharger speed slows as a lower volume of gas is produced.

(b) Charging mode

At high engine speeds, there is more energy generated by the turbine than is required by the compressor. Under these conditions, the excess energy can be used to recharge the energy storage for the next acceleration phase or used to power some of the electrical loads such as electrical air conditioners, music systems, etc., as shown in tables 2,3 &4. Development is underway for replacing battery energy storage with a supercapacitor which can be charged and discharged very quickly. [5]

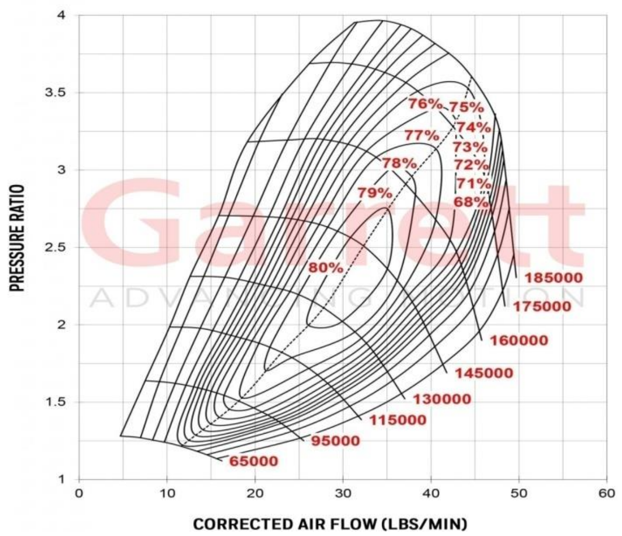
2. TURBOCHARGER SELECTION

Garrett turbocharger specification

Garrett
ADVANCING MOTION

	Mid Range RPM	Max Power RPM
Engine RPM	4500	7000
Power at crankshaft (HP)	181	349
Boost gauge pressure (PSI)	5.98	11.55
Pressure Ratio	1.47	1.84
Intake Manifold Temp (F)	42	49
Airflow, Corrected (Lb/Min)	15.37	29.74
Torque at crankshaft (Lb-Ft)	211	262
Moment of Inertia (Lb/Ft²)	0.00009216	0.00009216

SELECTED TURBO = G25-550



3. ENERGY ANALYSIS

3.1 Important Values and Symbols

- P2/P1 -Pressure Ratio- 1.84
- η - Isentropic Efficiency – 77.5 %
- Cpa - Specific Heat Capacity of Air at constant pressure [kJ/kg K]
- Cpa – 1.006
- Cpg - Specific Heat Capacity of Gas at constant pressure [kJ/kg K]
- Cpg - 1.17
- $\dot{m}a$ - Mass flow rate of air [kg/s] – 0.224
- Air-fuel ratio at peak power = 13:1
- $\dot{m}f$ - Mass flow rate of fuel [kg/s] – 0.224/13= 0.017
- $\dot{W}$ - Work or Energy flow rate [W]

- T - Temperature [K] C - Compressor
- I - Inertia [kg/m2] – 0.00045
- ω - Turbocharger rotational speed [rad/s] – 13083.33
- t - Time [s]
- Vt - Total Displacement [m3] – 2 L
- n - ICE rotational speed [rpm] - 7000
- p - Pressure [Pa]
- R - Gas constant [kJ/kg K]
- 0 - ICE inlet condition
- MGU-H - Motor – Generator Unit – Heat
- h - Enthalphy

3.2 Calculations

3.2.1 Compressor

Steady flow energy equation is given by,

$$\dot{W} = \dot{m}\,[h_{out} - h_{in}]$$

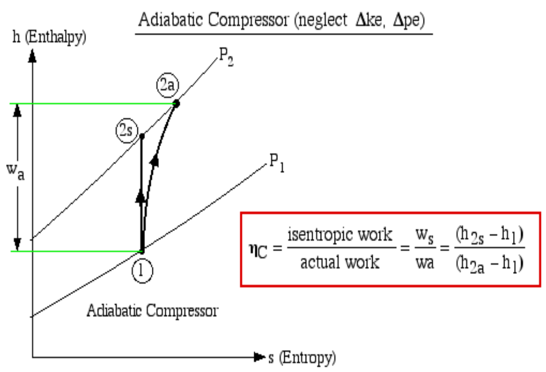


Fig. 1: H-S dia. For compressor

$$\eta_C = \text{Isentropic Work} / \text{Actual Work} = \dot{W}s / \dot{W}a$$
$$\dot{W}a = \dot{W}s / \eta_C$$
$$= [\, \dot{m}a\ Cpa\ (T2s - T1)] / \eta_C$$
$$= \dot{m}a\ Cpa\ T1 / \eta_C\ (T2s / T1 - 1)$$

As it is a isentropic process ;

$$T2s / T1 = [p2s / p1]^{(\gamma-1/\gamma)}$$
$$Pc = \dot{m}a\ Cpa\ T1 / \eta_C\ [\{p2s / p1\}^{(\gamma-1/\gamma)} - 1)] \quad \_\_ \quad (1)$$

keeping T1 = 303K; gamma= 1.4

Pc = 16.76559 KW

3.2.2 Turbine

h-S diagram for the turbine is given by

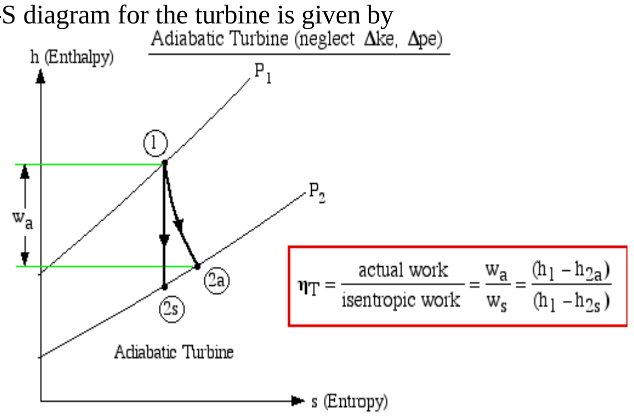


Fig. 2: H-S Dia. For Turbine

$$\eta_T = \text{Actual Work} / \text{Isentropic Work} = \dot{W}a / \dot{W}s$$
$$\dot{W}a = \dot{W}s * \eta_T$$
$$= (\dot{m}a + \dot{m}f)\ \eta_T\ Cpg(T1 - T2s)$$
$$= (\dot{m}a + \dot{m}f)\ \eta_T\ Cpg\ T1\ (1 - T2s / T1)$$

As it is a isentropic process,

$$T2s / T1 = (p2s / p1)^{\gamma-1/\gamma}$$
$$PT = (\dot{m}a + \dot{m}f)\ \eta_T\ Cpg\ T1\ [\ 1 - (p2s / p1)T^{\gamma-1/\gamma}\ ]\ (2)$$

Pt= 32.30262 KW

Energy Balance Equation:

$$\mathbf{PT - PC \pm PMGU\text{-}H = T\,\omega = I\,(d\,\omega /dt)\,\omega \quad (3)}$$
$$T\,\omega = 2.9952\ KW.$$
$$P\,(MGU\text{-}H) = 12.651\ KW.$$

4. CONCLUSION

This idea can be implemented in industrial and commercial automobiles for better efficiency and cost efficiency. The concept of regenerative systems can be executed in mass-produced vehicles. This can help reduce reliance on fossil fuels. MGU assisted turbocharger can be used in turbocharged engines. RBS can improve overall range of electric and hybrid vehicles.

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