# RECOVERY OF EXHAUST GASES ENERGY BY MEANS OF TURBOCOMPOUND

Bronisław Sendyka [1], Jacek Soczówka [2]
Politechnika Krakowska
31-155 Kraków, ul. Warszawska 24
tel.+48 126282642
fax.+48 126282642
e-mail:jaceksoczowka@op.pl

## Abstract

The paper gives an analysis of solutions of turbocompound action: mechanical and electrical. Traces of power obtained by the turbine and power demand for driving the air compressor are also shown. A graphic presentation of power that maybe recovered from exhaust gases energy by application of these systems is also given.

The last part of the paper contains conclusions on turbocompound systems and their advantages.

## 1.Introduction.

First air-craft engines with turbocompound were used already during the II World War. Then, they were used in marine engines. Since 1991 Scania Company has been producing trucks equipped with turbocompound engines.
In U.S.A. works are carried out on electrical systems of turbocompound.

Due to this device a part of exhaust gases energy is recovered and it permits to increase the general efficiency of the engine and improve the performance of the engines.

## 2. System of mechanical turbocompound work.

A classical turbocompound consists of a turbine and compressor. At low rotational speed of the engine when pressure of exhaust gases is not satisfactory the turbine causes some resistance the flow of exhaust gases and worsen the charge exchange. In order to present these unfavourable phenomena valves opening the exhaust gases wastegate that omits the turbo-compressor are applied. At higher rotational speeds and higher exhaust gases pressure, however, the turbine produces big enough amounts of energy to drive a compressor. The power produced by the turbine exceeds the amount required driving the compressor, hence it is reasonable to make use of it for driving a generator which is an additional source in the case of an electrical turbocompound and for direct transmission of power on to the shaft in the case of a mechanical solution. This is shown in fig. 1 which shows the power which maybe recovered by the turbine from outflow gases and the power demand for driving the compressor. The described diagram was made on the example of a Caterpillar C15.
Fig.2 presents the scheme of the structure of a turbocompound mechanical system and the way of its functioning. Exhaust gases which leave the engine (B) hit the turbine blades transference it a part of their energy. Exhaust gases are cooled there to about 600ºC. The turbine drives the compressor. The compressor presses the air (A) into the aircooler of the super-charged air. Subsequently the exhaust gases, having passed the turbine, come across an in series installed power turbine (2). There again they give away a part of their energy undergoing expansion and cooling by about 100ºC. In such a form the exhaust gases flow out of the power turbine entering the exhaust system (C). The power taken from the exhaust gases is transmitted on to the crankshaft of the engine through a hydrokinetic clutch (3) and toothed gear (4). Application of a hydrokinetic clutch was absolutely necessary with regard to rotational forces the power turbine rotor works at (at nominal pressure about 5000 rpm).

This engine compared with the same unit but not equipped with a turbocompound system and High Pressure Injection supply system shows a power greater by about 37 (kW) and maximal torque 2200 [Nm] at 1000-1400 [rpm] versus 1950 [Nm] at 1100-1550 [rpm] of a weaker unit.

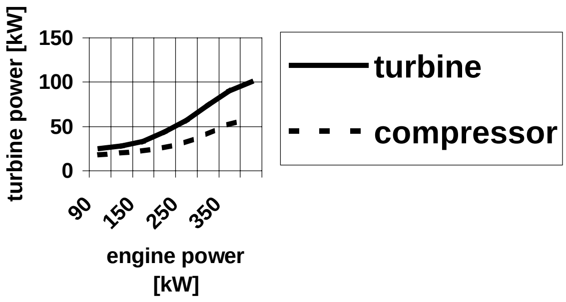



Fig.1. Characteristics of turbine and compressor power. The surplus of energy produced by the turbine in relation to compressor is clearly visible for the engine Caterpillar C15. [7]

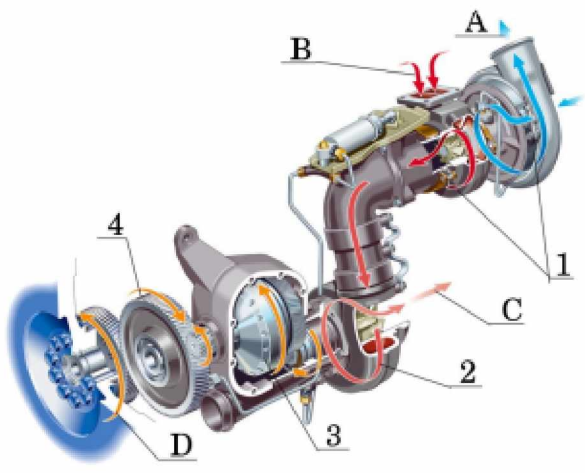



Fig.2. Scheme of structure of a turbocompound mechanical system 1- turbo-compressor, 2-power turbine, 3-hydrokinetic clutch, 4-toothed gear.
Functioning of this system: A- air is pressed by the compressor into the supercharged aircooler, B-exhaust gases blown on to the turbine blades undergo cooling and expansion giving away a part of its energy, C-exhaust gases, having passed the traditional turbo-compressor flow on to the power turbine where they still lose a part of energy, D-energy recovered from exhaust gases is transmitted by the gear system on to the crankshaft of the engine. [10]

The theoretical work of the turbine is described with the relation is described by equations (1), (2), [2], [3]:

$$l_0 = \frac{k_1}{k_1 - 1} \cdot R_{sp} \cdot T_s \cdot \left[ 1 - \left( \frac{p_s^{'}}{p_s} \right)^{\frac{k_1 - 1}{k_1}} \right] \text{[kJ/kg]} \quad (1)$$

$$\frac{T_s^{'}}{T_s} = \left( \frac{p_s^{'}}{p_s} \right)^{\frac{k_1 - 1}{k_1}}$$

$$l_o = \frac{k_1}{k_1 - 1} \cdot R_{sp} \cdot \left( T_s - T_s^{'} \right) \text{[kJ/kg]} \quad (2)$$

where:

$l_o$ – theoretical work

$k_1$ – exponent of adiabate exhaust gases

$R_{sp}$ – constant of exhaust gases

$p_s$ – pressure of exhaust gases behind turbine

$p_s^{'}$ – pressure of exhaust gases in front of turbine

$T_s$ – temperature of exhaust gases flowing into the turbine

$T_s^{'}$ – temperature of exhaust gases after leaving the rotor

The obtained equation defines the relation between the quantity of theoretical work in the turbine and drop of exhaust gases temperature after passing through the turbine.
The power obtained from the turbine can be described by the relation:

$$N_t = G_S \cdot l_t = G_s \cdot l_o \cdot \eta_t \, [W] \quad (3)$$

where:

$N_t$ – theoretical power $[W]$

$G_s$ – intensity of exhaust gases flow $[kg/s]$

$\eta_t$ – efficiency of the turbine (isentropic)

Flow intensity of exhaust gases maybe determined by means of air amount introduced by the compressor and coefficient of the molecular change of the factor which is determined with the formulae (3), [3], [6]:

$$\beta = \frac{m_{pow} + m_{pal}}{m_{pow}} \quad (4)$$

where:

$\beta$ – coefficient of the molecular change

and for supercharged Diesel engines it is within the limits 1,03÷1,05
Flow intensity of exhaust gases is described by equation (5):

$$G_s = \beta \cdot G_p \quad (5)$$

where:

$G_S$ – flow intensity of exhaust gases $[kg/s]$

$G_P$ – amount of air pressed into the engine cylinders $[kg/s]$

Amount of air entering the engine cylinders is described by equation (6):

$$G_p = \frac{n \cdot V_{ss} \cdot \eta_n \cdot \gamma_{pow}}{120} [kg/s] \qquad (6)$$

where:

$G_P -$ amount of air pressed into the engine cylinders $[kg/s]$

$V_{ss} -$ piston travel capacity of the engine $[m^3]$

$\gamma_{pow} -$ air density in conditions prevailing at the inflow to the cylinders (considering the supercharge degree) $[kg/m^3]$

$n -$ rotational speed of the engine $[rpm]$

$\eta_n -$ filling coefficient

On the basis of the presented calculational model (fig.3) the characteristics of the turbine power was determined:

-a calculational programme in Maple was elaborated,

-initial data were prepared on the basis of the engine characteristics,

-calculational result were transferred to the Excel programme by means of which the function of turbine power was plotted in dependence on the power attained by the engine at full load presented in fig.4..

Block scheme of the calculational system is shown on the Fig.3:

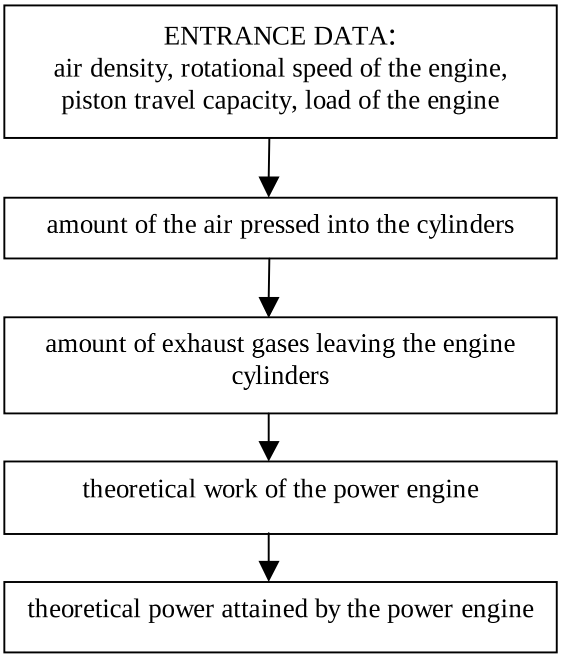



Fig.3. Block scheme with consecutive calculational stages of turbine power.[1],[2], [3]

**2.1Calculational programme in Maple language:**

1.Entrance data: air density, rotational speed of the engine, piston travel capacity:

```
> ypow:=1.128;nn:=1.1;Vss:=0.012;
```

$$ypow := 1.128$$

$$nn := 1.1$$

$$Vss := 0.012$$

2.Amount of air pressed into cylinders:

```
> Gp:=(n*Vss*nn*ypow)/120;
```

$$Gp := 0.0001240800000n$$

3.Amount of exhaust gases leaving the cylinders:

```
> B:=1.05;
```

$$B := 1.05$$

```
> Gs:=B*Gp;
```

$$Gs := 0.0001302840000n$$

4.Theoretical work performed by the turbine:

```
>
k1:=1.333;Rsp:=294,2;Ts:=700;Tss:=
600;
```

$$k1 := 1.333$$

$$Rsp := 294, 2$$

$$Ts := 700$$

$$Tss := 600$$

```
> Lo:=Rsp*(Ts-Tss)*(k1/(k1-1));
```

$$Lo := 117688.2883$$

```
> nt:=0.9;
```

$$nt := 0.9$$

5.Theoretical power obtained by the turbine:

```
> Nt:=(Gs*Lo*nt);
```

$$Nt := 13.79961086n$$

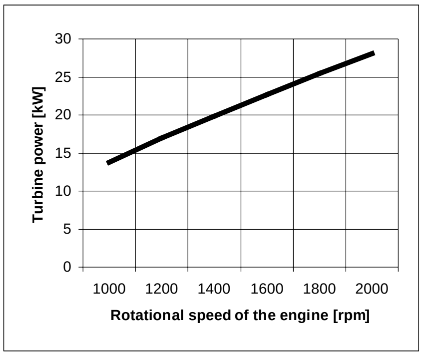



Fig.4. Traces of the function of power attained by mechanical turbocompound system .

Calculation results were transferred to the Excel programme by means of which the characteristics of the turbine power was plotted in dependence on the Scania engine power under full load which is shown in fig.5.

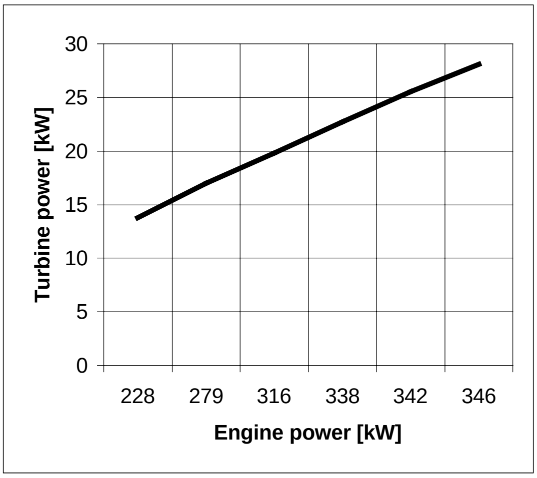



Fig.5. Traces of the function of power attained by mechanical turbocompound system in dependence on the power of the Scania engine DT12 02 470 on which it is mounted. [3], [4], [6], [10]

## 3.Electrical Turbocompound.

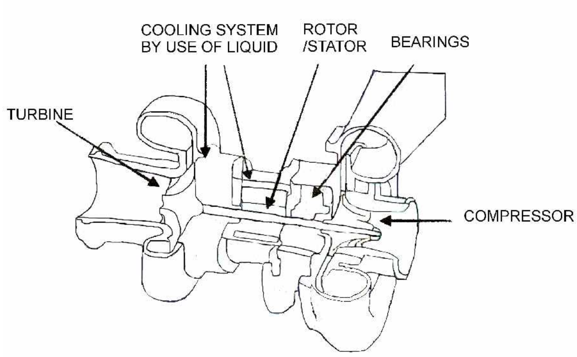
The firm Caterpillar elaborated a prototype system of an electrical turbocompound [7] presented in schematical form in fig.6.

The electrical turbocompound eliminates the mechanical connection with the crankshaft. This makes mounting of his system easier and moreover, this system requires less room.

The system of electrical turbocompound consisted an air compressor, turbine, and a generator mounted in between. The generator, with regard to hard work conditions is cooled with a water coat in a similar way it is done in the engine body.

The electrical generator may also work at low exhaust gases pressure as an electrical engine driving the compressor, and eliminating at the same time the basic drawbacks of a turbo-compressor: great delay in action and effective work only after a certain pressure of outflow gases has been exceeded.

Fig. 6. shows a section of turbocompound. It is a traditional turbo compressor in where the compressor is separated from the turbine by a generator and coat of a cooling medium.




Rys.7.Cross section of electrical turbo-serving.[7]

This system, similarly as its mechanical version, contributes to reduction of fuel consumption. This, however is clearly visible only at rotational speeds close to the maximal torque, thus, maximal outflow gases pressure. The ETC system ( Electric Turbocompound Caterpillar) permits to reduce fuel consumption in the whole range rotational speed from 5-10,3%. The highest value of fuel consumption reduction corresponds with the rotational speed at maximal torque. This is presented in fig.8.

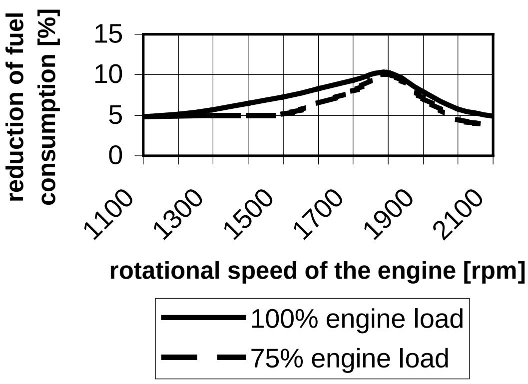



Fig.8. Reduction of fuel consumption [%] in comparison to the same engine without turbocompound.[7]

On the basis of a balance of the power recovered by the turbine from exhaust gases and demand for air compressor drive traces of power attained by the electrical turbo-serving system were plotted. The characteristics is made in function of power of the engine on which this system is mounted. This is shown in fig.9.

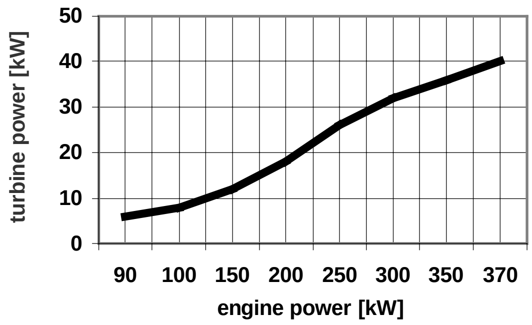



Fig.9. Characteristics of power of electrical turbocompound system in which the engine Caterpillar C15 was equipped. [7]

## 5.Conclusions.

A considerable part of the energy produced during combustion process in the engine cylinders escapes with exhaust gases. Due to the turbocompound system a part of this energy maybe recovered.
Application of these systems permits:
Increase in attained power even by 10-11%,
The torque increase as well by about 11%,
Fuel consumption is reduced by 5-11%.
Changes of these parameters occur in the whole range of engine work. Whereas, these changes are most noticeable at highest load when the engine works at rotational speeds close to the maximal torque.

It follows from these observations that application of a turbocompound system is profitable, especially for heavy loaded engines.

## 6.References.

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