

Waste Energy Driven Air Conditioning System (WEDACS)

R.H.L. Eichhorn, M.D. Boot, C.C.M. Luijten
Eindhoven University of Technology

Copyright © 2009 SAE International

ABSTRACT

In the port injected Spark Ignition (SI) engine, the single greatest part load efficiency reducing factor are energy losses over the throttle valve. The need for this throttle valve arises from the fact that engine power is controlled by the amount of air in the cylinders, since combustion occurs stoichiometrically in this type of engine.

In WEDACS (Waste Energy Driven Air Conditioning System), a technology patented by the Eindhoven University of Technology, the throttle valve is replaced by a turbine-generator combination. The turbine is used to control engine power. Throttling losses are recovered by the turbine and converted to electrical energy. Additionally, when air expands in the turbine, its temperature decreases and it can be used to cool air conditioning fluid. As a result, load of the alternator and air conditioning compressor on the engine is decreased or even eliminated, which increases overall engine efficiency.

A model and validating experiment both indicate throttle losses of about 1.25 kW in a modern 2 liter engine at common operating points. On the same engine in a different operating point, an automotive turbocharger is used in another experiment to recover 1.1 kW of these throttling losses. Based on these measurements, a simulated MVEG-A drive cycle predicts a fuel efficiency improvement of 15 to 19 %.

INTRODUCTION

The most predominantly used engine for passenger transport is the port injected SI engine, in which a premixed charge is ignited by a spark plug. The best compromise of efficiency and emissions is found around stoichiometric combustion. As a consequence, engine

power is controlled by the amount of air in the cylinders. Usually this is done by partially closing a throttle valve in the inlet manifold. Along with the air mass flow rate, the pressure is reduced over this valve, resulting in negative work of the engine during intake (called throttling loss). At part load, when the throttle valve is closed, throttling losses are high. So when the engine has to deliver low output power, it has to overcome high throttling losses, decreasing the efficiency at part load considerably.

A number of attempts have been made to address this problem. The most well-known solution is direct injection, where engine power is controlled by injecting less fuel, resulting in a lean charge [1]. BMW's Valvetronic is a less drastic solution [2]. It can vary valve lift and control engine power in this way, retaining stoichiometric combustion. It makes the throttle valve obsolete and reduces throttle losses to some extent. At idle, losses are reduced by 23 %. Also a turbine-generator combination replacing the throttle valve has been investigated before [3]. At the Swiss Federal Institute of Technology, an axial turbine with adjustable stator blades coupled to an electric generator is used. The cooled air is heated again using engine coolant. During the experiment, electrical energy produced by the system was 1.6% of energy consumed by the vehicle over an MVEG-95 drive cycle. WEDACS is different in using cold air behind the turbine to cool air conditioning fluid, resulting in a further increase in overall fuel efficiency.

This paper is based on research that was carried out with two goals in mind. The first is to quantify throttling losses for a given engine. A simple model will be introduced and validated by a throttle loss experiment. The second goal is to prove the WEDACS concept. An energy recovery experiment is conducted and its results are used to simulate an MVEG-A drive cycle with and without WEDACS in place.

In the first section the WEDACS system is introduced. Next, the theory behind the model, experiments and drive cycle is addressed, followed by a description of the experiments themselves. Finally, results are presented and discussed.

SYSTEM DESCRIPTION

WASTE ENERGY DRIVEN AIR CONDITIONING SYSTEM (WEDACS) - WEDACS is an engine load control system that as an addition provides electrical energy and cooling power, driven by energy that is otherwise lost in throttling. As explained in the introduction, at part load operation the engine has to do extra work to keep running and maintain a partial vacuum behind the partially closed throttle valve. These throttling losses form the waste energy WEDACS uses.

The throttling valve is replaced by a turbine which, in contrast with the throttling valve, is able to produce work from the pressure drop across it. This work is transferred through a shaft to a compressor or alternator. In the case of an alternator, work is turned into electrical energy. This means that, at part load, the conventional alternator can be disconnected from the engine.

By expansion across the turbine, the air is cooled down substantially. This air can flow through a heat exchanger and cool the air conditioning fluid. This reduces the power consumed by the compressor in the air conditioning system, which is 1.5 to 3.5 kW for a full size passenger car [4, pg. 231].

Disconnecting the conventional alternator and lower power consumption by the air conditioning compressor means that the engine can produce less power. Now these accessories are driven by power produced by the conversion of throttling losses. The engine has to burn fuel to overcome these losses anyway, so now this fuel is put to good use, at the same time saving the fuel that would otherwise be burnt to drive the alternator and air conditioning compressor.

The elegance of this system is contained in the fact that by rerouting one stream of energy, two sources of extra efficiency are created: first, energy is extracted from the air and transferred to an alternator; and second, the cold (less energetic) air is used to cool air conditioning fluid.

An extra advantage would be the following (although this is not further substantiated in the present paper). When cold air passes through the heat exchanger, it not just cools the air conditioning fluid, but also the heat exchanger itself. The result is a cold mass. When the car suddenly accelerates, air does not move through the turbine anymore. It moves through a bypass, but still passes the heat exchanger. Being cold, the heat exchanger cools down the air. This temporarily increases the engine's volumetric efficiency (thus power), up to the point where the heat exchanger mass has warmed up to ambient air temperature again.

The main components of the system (the turbine and the alternator) are described below.

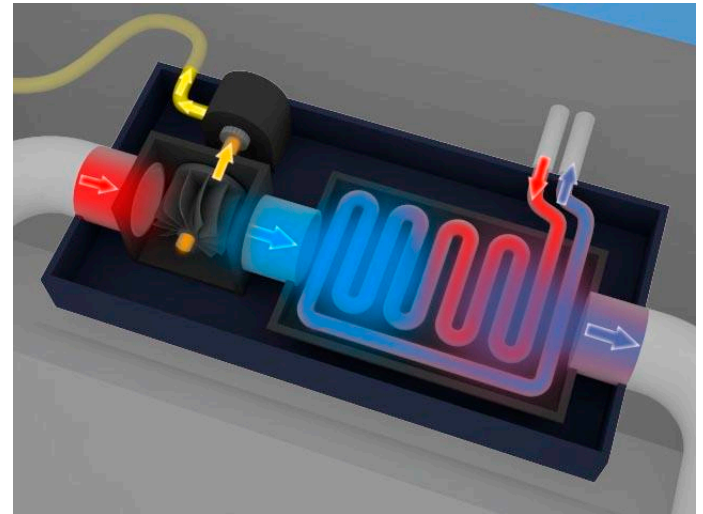


Figure 1: Schematic view of WEDACS operation. Red denotes “ambient”, blue denotes “cold”; yellow is electricity.

TURBINE - The turbine is the core component of WEDACS, it extracts energy from the intake air. The turbine is of the radial inflow type to be able to handle the low and diverse air mass flow rates encountered in the intake of the engine. This type is also found in turbochargers, where it extracts energy from the engine's exhaust gases to drive a compressor. One can imagine that the turbine is in a much more friendly environment in the engine's inlet. In the exhaust it has to withstand temperatures of over 800 °C and soot deposits. Therefore, a turbine in the inlet can be made much cheaper than an exhaust turbine.

For every mass flow within a certain range, the turbine can produce one pressure ratio. By varying the rotational speed at this mass flow rate, the pressure ratio can be varied a little. This can be seen in the turbine characteristic map in figure 2, where lines are plotted for several values of rotational speeds. These speeds can vary from 50.000 to 150.000 rpm. When mass flow increases, rotational speed increases and higher pressure ratios are possible. Another graph is plotted in figure 3 indicating turbine efficiency for the same operating points. It is clear that at a certain rotational speed, the efficiency decreases when the pressure ratio increases. Generally, efficiency also decreases when rotational speed increases. When rotational speed can be controlled, air mass flow rate and turbine efficiency may be varied to some extent for a single pressure ratio.

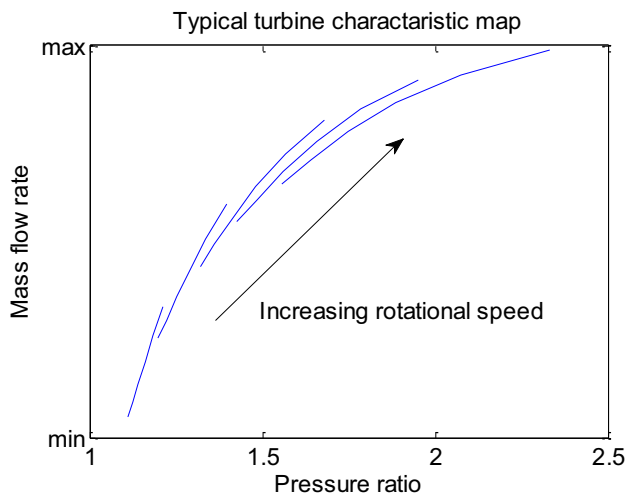


Figure 2: Turbine characteristic map, every line denotes a single rotational speed

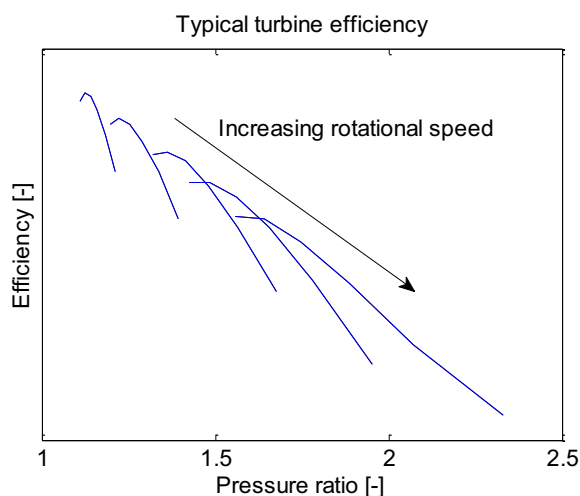


Figure 3: Turbine efficiency map, every line denotes a single rotational speed

ALTERNATOR - The most straightforward use for the mechanical energy coming from the turbine is to convert it to electrical energy. This is done using an alternator. The alternator is a common part on every internal combustion engine, where it produces electrical energy e.g. for the ignition system and engine control system. This alternator runs at speeds of around 10.000 rpm and typically has a low efficiency. For these reasons, it is not suitable to be coupled to a turbine, which can run at speeds in excess of 100.000 rpm. An alternative is found in DC motors, which can also be used as alternators. These motors consist of a permanent magnet rotor and a stator containing coils. High speed alternators of this type are available with maximum speeds of over 100.000 rpm. In addition these are very small, lightweight and have an efficiency of 90 to 97 % [5].

WEDACS/ENGINE INTERACTION - In the complete system, the components treated above will be coupled to each other in one single housing. The turbine and alternator will run on a common axis that is suspended in bearings. The turbine cannot provide the right air mass flow and pressure drop in the entire engine operating

range. For example, the air mass flow at idle might be out of range for the turbine. This is why a throttle valve might have to be mounted in series with the turbine. Another problem is the engine's wide open throttle operating point. To make this possible, the air should be led around the turbine. A bypass with a throttle valve in parallel with the turbine would have to be made. The air flow paths of the system introduced above are shown in figure 4.

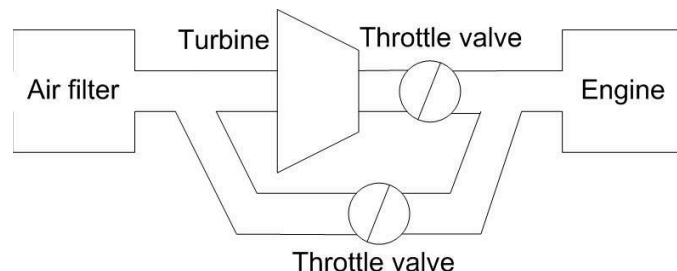


Figure 4: Air flow paths in the WEDACS system

The system of turbine and throttle valves has to replace a single throttle valve. When installed in a car the driver should not notice the presence of the system. This is accomplished by sizing and calibration. Air mass flow and pressure drop across the system are equivalent to that over the single throttle valve. There is another effect however, caused by the turbine. The air going into the engine is much colder and can be well below freezing point of water. This causes water in the air to condense and even freeze. The water drops that are formed absorb injected fuel and can change the air/fuel ratio in the cylinders. This can have a negative effect on combustion. In modern engines, fuel is injected directly on the intake valve or inside the cylinder, so condensation of water does not seem to have an effect. Special attention has to be paid to temperatures of moving components that are exposed to the cold air. For example throttle valves can get stuck by freezing.

The cooling of air does not only have negative effects; it also reduces the tendency of knocking. The temperature of the mixture in the cylinder before combustion is directly related to its intake temperature. Lowering the latter directly reduces the risk of knocking. This can be put to an advantage in several ways.

First, ignition can be advanced, resulting in an optimized combustion phasing and hence higher efficiency.

Second, WEDACS can have an advantage in variable compression ratio engines. When these engines become available in the near future, WEDACS allows an additional increase in compression ratio at part load because of lower intake temperature. This increase in compression ratio raises the engine efficiency.

THEORY

In this section, throttling losses over the engine operating range are quantified. A model is made to predict these losses. The model aims to predict air mass flow rate, pressure drop and losses over the throttle valve. Next, equations used to process data from the throttle loss experiment are introduced. Theory used to process data from the energy recovery experiment is treated and finally the drive cycle simulation is explained.

THROTTLE LOSS MODEL - A very simple model is made to quickly predict throttling losses for a specific engine. In the process of calculating throttling losses, also air mass flow and pressure drop over the throttle valve are calculated, which are very important variables when matching a turbine to an engine.

The starting point of this model is a brake specific fuel consumption (BSFC) map of a 2 liter gasoline engine. This reference map belongs to a 2 liter Ford engine [6]. An impression of this map is made in Matlab to be able to use it for the following calculations. The real map and the digital impression can be seen in figures 5 and 6.

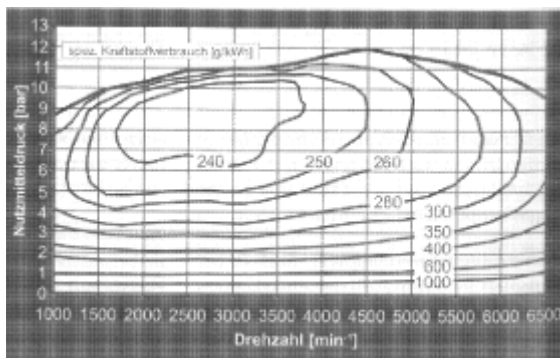


Figure 5: BSFC map of 2 liter Ford engine, y-axis is a mean effective pressure [6].

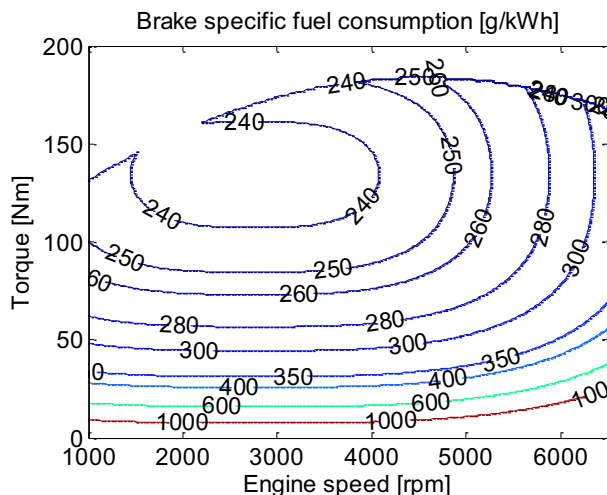


Figure 6: Digitalized "reconstructed" BSFC map, y-axis is converted to engine torque

When looking at the values of fuel consumption on the contour lines, it can be seen that the digital map is a fair representation of the original map. At low engine speeds near the maximum torque line, the reconstructed map deviates by at most 16 %, caused by the nature of the function used to generate the curves. At part load, which is the area of interest, the maps are almost identical.

Air mass flow rate - To calculate the air mass flow in every point in the BSFC-map, the assumption is made that combustion is always stoichiometric. First, fuel consumption is calculated by multiplying specific fuel consumption by engine power,

$$\dot{m}_f = BSFC \cdot T_e \cdot \omega / 3.6 \cdot 10^6, \quad (1)$$

where $\dot{m}_f$ is fuel mass flow in g/s, $BSFC$ is brake specific fuel consumption in g/kWh, T_e is torque in Nm and ω is engine speed in rad/s. From fuel mass flow, air mass flow is calculated assuming stoichiometric combustion,

$$\dot{m}_a = AF_s \cdot \dot{m}_f, \quad (2)$$

where $\dot{m}_a$ is air mass flow in g/s and AF_s is the stoichiometric air-fuel ratio, which is 14.5 for gasoline.

Pressure drop - To calculate the pressure drop over the throttle valve, the following formula can be used,

$$\dot{V} = \eta_{vol} \frac{V_d \cdot \omega}{4\pi}, \quad (3)$$

where $\dot{V}$ is the air volumetric flow rate in m³/s, V_d is the engine swept cylinder volume in m³ and η_{vol} is the volumetric efficiency. To calculate the volumetric flow, an assumption has to be made for volumetric efficiency. A correlation for volumetric efficiency of various multi-cylinder Otto engines [7, pg. 192] is plotted as a function of engine speed in figure 7, and used in the model. The air density behind the throttle valve can be calculated using,

$$\rho_{bv} = \frac{\dot{m}_a}{\dot{V}}, \quad (4)$$

where ρ_{bv} is the density of air behind the throttle valve in kg/m³. Using this air density, the pressure in the inlet manifold can be calculated using the ideal gas law,

$$p_{bv} = \rho_{bv} RT, \quad (5)$$

where p_{bv} is the pressure behind the throttle valve in Pa, R is the gas constant of air (287 J/kg/K) and T is the intake temperature in K, assumed to be 300 K.

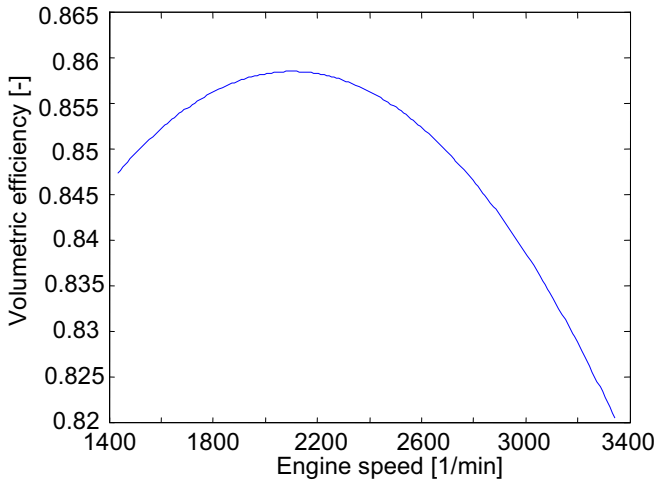


Figure 7: Volumetric efficiency versus engine speed [6].

Throttling losses - The power that is lost in the throttling process and thus available to the turbine is,

$$P_{throt} = (p_{atm} - p_{bv}) \cdot \dot{V} = \Delta p \cdot \dot{V}, \quad (6)$$

where p_{atm} is atmospheric pressure in bar and P_{throt} is the power that is dissipated by the throttling process.

THROTTLE LOSS EXPERIMENT - Power lost in the throttling process can be calculated in a way similar to that in the simulation.

$$P_{throt} = \Delta p \cdot \dot{V} = \Delta p \cdot v \cdot \dot{m}_a, \quad (7)$$

where the pressure drop Δp can be calculated with

$$\Delta p = p_{fv} - p_{bv}, \quad (8)$$

and v , the specific volume in m^3/kg , can be calculated by the ideal gas law:

$$v = \frac{1}{\rho} = \frac{RT_{bv}}{p_{bv}}, \quad (9)$$

where T_{bv} is the temperature behind the valve. The density in this formula, and thus the pressure and temperature, is that of the air behind the throttle valve. These pressures, temperatures and air mass flow rate are all measured variables.

ENERGY RECOVERY EXPERIMENT - The amount of power recovered by the turbine can be calculated from the temperature drop and air mass flow rate through the turbine with:

$$P_t = \dot{m}_a \cdot C_p \cdot \Delta T_t, \quad (10)$$

where C_p is the specific heat of air (1005 J/kg/K) and ΔT_t is the temperature drop over the turbine.

Effect of condensation - The turbine extracts a fixed amount of energy from a certain pressure drop and a certain mass flow rate of air. This causes a temperature drop over the turbine, the value of which depends on the energy extracted by the turbine. At some point water present in the air will condense, releasing thermal energy (latent heat). This energy heats up the air again and thus compensates part of the temperature drop. Therefore, when looking at the temperature drop during condensation, the energy recovered by the turbine seems to be lower than it actually is.

How large the energy involved in condensation is, depends on the amount of water vapor present in the air and how much of that condenses. To specify how much water is present in the air, two variables are used; specific (ξ) and relative humidity (ϕ). The relative humidity on the days of the measurements was about 60 %. To calculate the mass of water present in the air, first the specific humidity is calculated:

$$\xi = \frac{0.622 \cdot \phi \cdot p_g}{p - \phi \cdot p_g}, \quad (11)$$

where p is the total pressure and p_g is the saturated vapor pressure. The number 0.622 comes from the ratio of gas constants from air and water vapor. Next the mass of water present in the air can be calculated:

$$m_v = \xi \cdot m_a \Rightarrow \dot{m}_v = \xi \cdot \dot{m}_a, \quad (12)$$

where m_v is the mass of water vapor and m_a is the mass of air. At a temperature of 20 °C, the saturated vapor pressure of water is 2.34 kPa and with a relative humidity of 60 %, one kg of air contains 8.8 g of water vapor.

The saturation pressure drops with decreasing temperature. Initially, the mass of water vapor in the air will be constant, so the relative humidity will rise as the saturated vapor pressure drops (see equation 11). When the relative humidity reaches 100%, a further temperature drop will cause water vapor to condense. It is assumed that the relative humidity will stay at 100%.

The specific humidity, i.e. kg's of water vapor in one kg of air, is plotted as a function of decreasing temperature in figure 8. The starting point is 20 °C with a relative humidity of 60 %.