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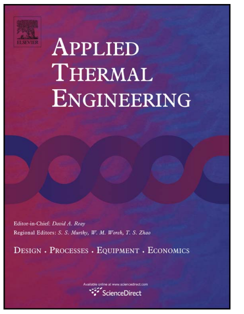

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Thermal Efficiency Improvement in High Output Diesel Engines A Comparison of a Rankine Cycle with Turbo-compounding

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Thermal management, in particular, heat recovery and utilisation in internal combustion engines result in improved fuel economy, reduced emissions, fast warm up and optimized cylinder head temperatures. Turbocompounding is a heat recovery technique that has been successfully used in medium and large scale engines. Heat recovery to a secondary fluid and expansion is used in large scale engines, such as in power plants in the form of heat recovery steam generators(HRSG)[1]. The present paper presents a thermodynamic analysis of turbocompounding and heat recovery and utilisation through a fluid power cycle, a technique that is also applicable to medium and small scale engines. In a fluid power cycle, the working fluid is stored in a reservoir and expanded subsequently. The reservoir acts as an energy buffer that improves the overall efficiency, significantly. This paper highlights the relative advantage of exhaust heat secondary power cycles over turbocompounding with the aid of MATLAB based QSS Toolbox [2] simulation results. Steam has been selected as the working fluid in this work for its superior heat capacity over organic fluids and gases.

1. INTRODUCTION

Exhaust gas heat utilisation in internal combustion engines has attracted a major interest due to the substantial potential of the amount of heat that can be recovered[3]. Exhaust heat utilisation cycles for internal combustion engines can improve the fuel efficiency and reduce carbon emissions of conventional engines. These cycles can have different configurations and use a number of working fluids. Studies on turbines, vane rotors, and Wankel engines that use steam and organic compounds as working fluids are found in literature [4]. The most promising and technically viable technologies are however, turbo compounding and exhaust heat secondary fluid power cycles. As a exhaust heat utilisation technique, turbo-compounding is already established in heavy duty engines [5], where a reduction in exhaust gas temperature is the consequence of an additional stage of expansion through an exhaust gas turbine. Small scale fluid power systems running on a Rankine cycle, for example can implement continuous exhaust heat utilisation cycles for both heavy and light duty engines. This represents another means of extracting energy

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from the exhaust gas stream. For light duty applications, the fluid cycle can utilize stored thermal energy after prolonged high load conditions at a time when the traction engine may be switched off. In heavy duty engines, the cycle will simply provide a means of recovering exhaust energy and thereby boost the vehicle's fuel economy. With a heat storage such as a steam accumulator, the energy can be used to meet hotel loads in long haul trucks and in agricultural vehicles. A theoretical comparison of turbo-compounding and exhaust heat steam Rankine cycles is presented in this paper, supported by simulation results.

2. THEORETICAL ANALYSIS
Heat Recovery and Expansion vs Turbo-compounding

The two waste heat recovery techniques, exhaust heat secondary fluid cycle and turbo-compounding can be analyzed theoretically to compare the effectiveness of each method through a second law study. In turbo compounding, exhaust gases are directly expanded through a turbine forming a part of a Brayton cycle. Alternatively, if heat is recovered to another working fluid for example, into water or into an organic fluid, the resulting vapour can then be expanded through a fluid expander. The efficiency of the exhaust heat secondary fluid power cycle depends on the combined effectiveness of heat recovery (utilisation) method and the expansion cycle [6]. Our approach adopts an exergy based analysis of the two energy recovery methods. In the T-s diagram in figure 1, 1-2 represents

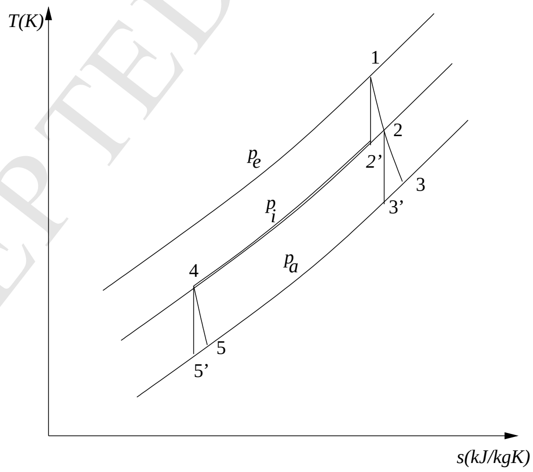

Figure 1. T-s diagram for heat recovery and utilisation options

the expansion of exhaust gases in the existing turbocharger. The exhaust gases at 2 can either be expanded to 3 or can be used to recover heat to use in another step. The exhaust gases follow the line 2-4 when the heat is recovered through a heat exchanger, and 4-5 if further expanded at lower temperature. A typical example of exhaust gases that come out of an internal combustion engine at 1.5 bar and 400^o C (i.e. at 2)is considered for expansion and exhaust heat utilisation. The available energy through heat recovery can be calculated as follows; Assuming a heat transfer effectiveness of 0.8 through a counterflow heat exchanger illustrated in figure 2. Effectively, ϵ is defined as:

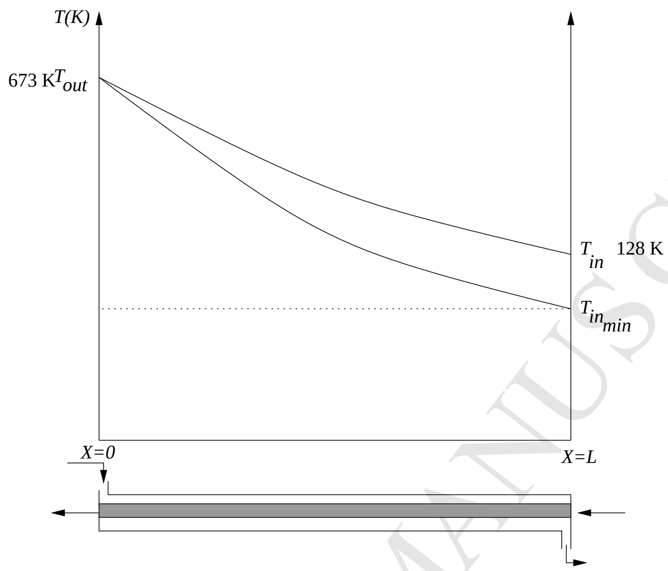

Figure 2. A typical counterflow heat exchanger arrangement in exhaust gas heat recovery

$$\epsilon = \frac{T_{out} - T_{in}}{T_{out} - T_{in_{min}}}, \tag{1}$$

using the following statement of the 1^{st} law, and

$$Tds = dh - vdp. \tag{2}$$

assuming that heat transfer at constant pressure through the heat exchanger, the change in entropy is given by

$$Tds = c_p dT, ds = \frac{1}{T} c_p dT \tag{3}$$

For the conditions given above, the change in entropy is

$$\int_{T_4}^{T_2} \frac{c_p}{T} dT = c_p \ln \frac{T_4}{T_2} = 520 J/kgK, \tag{4}$$

in our case $T_4 = 401$ K and $T_2 = 673$ K. The available work per unit mass is given by

$$\Delta b = \Delta h - T_0 \Delta s. \tag{5}$$

The available energy through exhaust heat recovery is 120kJ/kg. Figure 2 shows the relevant temperatures in the heat transfer from exhaust gases to steam. Further, 44 kJ/kg are available for expansion after heat recovery in the exhaust of the heat exchanger. An isentropic efficiency of 0.8 reduces this value to 35 kJ/kg. These figures add together to give a value of 155 kJ/kg through expansion through a secondry fluid power Rankine cycle. When direct expansion of gases in the turbine is considered from the initial conditions given earlier, the turbine exit temperature is given by

$$T_3 = T_2 \left[\frac{p_3}{p_2}\right]^{\frac{\gamma-1}{\gamma}} \tag{6}$$

where, T_2 is the inlet temperature to the turbine, for an inlet temperature of 673 K and a pressure ratio of 1.5, the exit temperature is 599K. The energy developed therefore, is 75 kJ/kg. An isentropic efficiency of 0.8 reduces this value to 60 kJ/kg as the total energy recovered through turbo-compounding.

The above illustrates shows that exhaust gas secondary expansion yields considerably higher amounts of energy than turbo-compounding for the same inlet conditions and outlet pressure. It is assumed that the heat transfer rates of both the schemes are adequately fast and similar.

3. SIMULATIONS AND RESULTS

We proceed to make drive cycle simulations of the two engine configurations.

3.1. Simulations

The QSS (quasi static simulation)[2] toolbox was used to emulate an engine with turbo-compounding and another with heat recovery and expansion through a steam expander. Both engine systems were driven through a US Federal Heavy Duty Transient Test Cycle. Simulations confirm the findings of the above calculations and show that considerable savings of fuel can be made using heat recovery and expansion method compared to turbo compounding. The following tables and graphs show the power developed by each exhaust heat utilisation system,the power developed by internal combustion engine, and in each case, the fuel savings. Figure 3 shows a schematic of the vehicle model in QSS. A backward facing one dimensional calculation procedure is used in QSS.

3.2. Power Output and Fuel Saving Comparisons

The power developed by each bottoming cycle is illustrated in table 1. At least two percentage points of more power can be developed with the exhaust heat utilisation secondary fluid power system compared to turbo-compounding. Based on the values obtained through simulations, Exhaust heat utilisation steam hybrid can result in fuel savings of 20% or more compared to around 2.5% savings with turbo-compounding.

The question arises as to how a 7.8% increase in power leads to a 22%increase in fuel economy. This can be explained in terms of the heat storage ability of the exhaust heat secondary fluid power cycle. The 'response' to temeperature fluctuations in a turbo compounding cycle is inferior to a heat recovery and expansion cycle. When the engine is heavily loaded, the extra energy wasted is recovered and stored in the secondary fluid reservoir. The secondary fluid (in this case steam) reservoir that is intricsic to the cycle acts as an energy buffer. All the energy that is recovered is not consumed immedieately, but is stored and expanded smothly on demand. This feature gives the ability to keep the

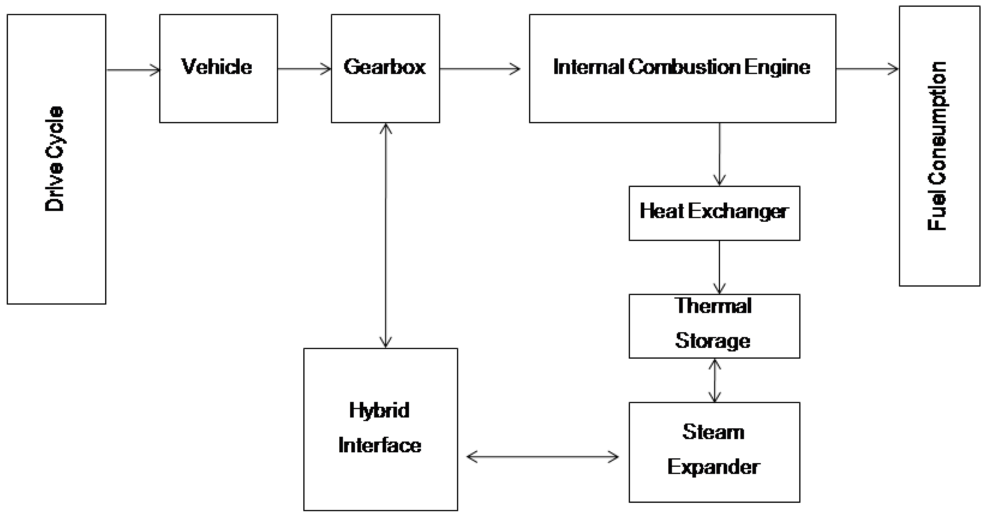

Figure 3. A schematic of QSS toolbox vehicle model

overall efficiency at a maximum. On the other hand, in turbo compound cycle, the enrgy recovered is limited by the top temperature and maximum flow rate through the turbine limiting the overall efficiency. This is a significant difference that makes heat recovery and expansion cycles favoured against turbocompound systems, and even against conventional electric hybrids. The main aim of the present study is to highlight this feature and the relative advantage of having an 'energy buffer' in the form of a steam storage. The added weight of a turbo compounding system of a Scania production engine that uses an electric turbocompound device is in the order of 80 kg (Scania press release) whereas a comparable Rankine cycle secondary fluid power system would weigh around 100 kg (see table 3). The weight of a mechanical turbocompound drive of a Caterpillar engine would also be in the same order.

While introducing the concept, it is important to discuss the negative effects of the technology. One major point is the use of a fluid power system that uses a secondary fluid. This means an added fluid power circuit to the vehicle system that adds another parameter to the complexity. As a general rule, dry technologies are preferred opposed to fluid power systems. However, air conditioning circuits have served extremely well over the past twenty to thirty years as an integral part of the engine. A secondary fluid power system, arguably would have the same degree of complexity as an air conditioning system. Another challenge is employing a relatively high pressure steam reservoir and a circuit. The technology is however, available. The expanders that are to be used are small scale steam expanders. This is relatively an underdeveloped area. University of Sussex has already carried out a few trials using small scale steam expanders and the results look favourable.

Table 1
Power output comparison

Simulation	Power (kW)
Truck with Caterpillar 3126 engine	37.23
Truck with steam hybrid (*total power*)	37.23
(*engine power*)	34.3
(*recovered power*)	2.93
% contribution	(7.8%)
Truck with turbocompound hybrid (*total power*)	37.23
(*engine power*)	35.69
(*recovered power*)	1.54
%contribution	(4.1%)

Table 2
Fuel savings comparison

Simulation	Fuel Used (l/100 km)	Saving (%)
Truck with 3126 engine	4.1962	0.0%
Truck with steam hybrid (*total*)	3.2675	22.0%
Truck with Turbo compound hybrid (*total*)	4.1215	2.0%

4. CONCLUSIONS

This communication highlights the applicability of exhaust heat utilisation through secondary fluid power cycles to internal combustion engines and its potential gains. A theoretical comparison backed by simulations show that heat recovery and expansion using steam as the working fluid can offer substantial gains in fuel economy, potentially in the order of 20%, compared to much established turbo-compounding. This is a very attractive figure even compared to other developed hybrid techniques. Considering fuel economy as the primary gain, there are other gains in the form of improved power on demand and lowered carbon emissions.

The future potential of exhaust heat secondary fluid power cycles depend on the ease of adaptability and the savings obtained. The technique of using heat recovery and expansion is very promising [7]due to its relative simplicity and attractive weight. Modifications to conventional engines are possible with a modification to the exhaust system. Future engines may be designed with better packaging of the secondary fluid power system. The energy harnessed can be used to give auxiliary power systems or to drive the electrical appliances, potentially replacing the alternator. This brings about the complexities of engine management and exhaust temperature control. A conventional IC engine and

Table 3
Added weight comparison of turbo-compounding and heat recovery fluid power cycles

Scania - electric turbo compound		Caterpillar turbo compound		Heat recovery fluid power cycle	
Component	Weight (kg)	Component	Weight (kg)	Component	Weight (kg)
Turbine	20.0	Turbine	20.0	Expander	6.0
Compressor	20.0	Compressor	20.0	Pump	5.0
Electric motor	30.0	Gear train	30.0	Gear train	20.0
Clutch	5.0	Clutch	10.0	Working fluid	25.0
				Condenser	10.0
				Heat exchanger	30.0
Auxiliaries	10.0	Auxiliaries	10.0	Auxiliaries	10.0
Total	85.0	Total	90.0	Total	106.0

a exhaust gas secondary fluid power cycle attachment will form a hybrid system that is analogous to an electric hybrid system. This approach will become more attractive due to its greener nature that favours it against electric hybrids that has an environmental issue with battery disposal in addition to the added weight. The added weight by a Rankine cycle hybrid system which is around 100 kg will be comparable to turbo-compounding attachment.

An exhaust heat secondary fluid power hybrid system will give the added advantage of being a heat storage system. The heat recovered can be used in the same way as in an electric hybrid to start from rest to save energy and to obtain high torque. Meeting hotel loads in heavy duty engines is another potential application wherereplacing electric and fuel cell auxiliary power units.

It is also noted that the performance figures depend on the drive cycle. In practical terms, this means that the performance changes according to terrain. Studies have been done on FTP US-06 and NEDC drive cycles[8] and they have shown promising potential.

This study opens the avenues for research in several areas. Optimization of the heat recovery mechanism, the control of the engine parameters for best fuel economy and emissions, and other hybridization issues such as the physical configuration, response analysis with drive cycles and implementation issues. Research is already being done on optimized heat exchanger design [9] and control of the hybrid system[10]. The selection of the working fluid of such a system is critical [11], but current research primarily focuses on steam due to the high heat capacity of water compared to organic fluids. Engine thermal and fuel control are major areas that require an object oriented approach in optimizing.Other technical areas of exploration are control issues in the form of engine control, heat recovery control and hybrid control. Research is already under way in most of these areas. University of Sussex is engaged in the development of [8] steam expanders, and control of an optimized steam hybrid system.

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