

An Assessment of the Bottoming Cycle Operating Conditions for a High EGR Rate Engine at Euro VI NOx Emissions

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ABSTRACT

This paper investigates the application of a Bottoming Cycle (BC) applied to a 10-litre (L) heavy duty Diesel engine for potential improvements in fuel efficiency. With the main thermodynamic irreversibility in the BC due to the temperature difference between the heat source and the working fluid, a proper selection of the working fluid and its operating condition for a given waste heat is the key in achieving high overall conversion efficiency. The paper reviews a fluid selection methodology based on thermodynamic/thermo-physical and environmental/safety properties. Results are presented using seven pure, dry, isentropic and wet working fluids (synthetic, organic and inorganic) operating with expansion starting from the saturated vapour, superheated vapour, supercritical phase, saturated liquid, and two-phase.

Efficiency improvements by recovering Charge Air Coolers (CAC) and Exhaust Gas Recirculation (EGR) cooler heat on two engine platforms were calculated. The first platform operating at Euro 6 engine out NOx emissions levels and the second platform operating with Euro 5 engine out NOx emissions coupled with a 80% efficient selective catalytic reduction system. Performance and heat rejection data for the 10L platforms were derived from experimental measurements on an advanced 2L single cylinder research engine which was used to determine the trade-off between thermal efficiency and regulated/unregulated emissions. Results indicate a potential improvement of 5.1% and 6.3% in engine power for a cruise (B50) and high load (C100) condition, with a technically feasible BC operating at subcritical mode with minimum superheat.

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INTRODUCTION

The impact of increasing fuel prices, regulated emissions, and CO₂ emissions have all increased the significance of exhaust Waste Heat Recovery (WHR) to improve engine Break Specific Fuel Consumption (BSFC). One method for WHR is the adoption of fluid driven Bottoming Cycles (BC). For WHR applied to Heavy Duty Diesel Engine (HDDE) major manufacturers and powertrain developers including Cummins, AVL, Volvo and Ricardo are exploring BCs. For maximum improvement, Cummins [1] and AVL [2] both initially conducted a case study showing an additional 15.3% and 20% of engine shaft power recovered through the BC, respectively. More recently, Cummins has applied its first generation recuperated R245fa Organic Rankine Cycle (ORC) to a US 2010 Cummins ISX (15L, 6-cylinder) HDDE. Using the heat from Exhaust Gas Recirculation (EGR) and the exhaust streams, a 7.4% fuel efficiency improvement

across the Heavy Duty Corporate Composite operating cycle was demonstrated [3]. AVL has applied a superheated recuperated ORC demonstration unit to 10.8L HDDE operating with ethanol as the working fluid. The results of EGR and exhaust heat recovery at high load (C100) generated 9.12 kW, resulting in a fuel consumption improvement of only 3% [4]. The reason for reduced BSFC improvements was due to the low operating pressure ratio of the modified GT-25 turbocharger (used as expansion device) and low EGR flow rates (10%). Volvo has also selected ethanol as the working fluid and are intending to use a piston expander. They simulated a parallel EGR and exhaust WHR topology, resulting in 9.9 kW at the B50 (7% of engine power) and 24.5 kW at the C100 (8.5% of engine power) condition [5]. Southwest Research Institute modelled a Rankine cycle, first using exhaust heat and then high temperature EGR heat. With 25-30% EGR flow and

Table 1. Applied NO_x strategy for EGR only and EGR focused platforms to meet Euro 6 emissions, and the resulting waste heat quantity and quality for the 10L engine models.

Test point (RPM/Torque)	Air to fuel ratio	Inlet (bar)	Inlet (°C)	EGR fraction (%)	Start of injection (BTDC)	Injection duration (°CA)	Fuel rail pressure (bar)	Inter-cooler kW [°C-°C]	After-cooler kW [°C-°C]	EGR kW [°C-°C]
EGR Only,B50, (1500/970Nm)	21.3	2.7	61	42.7	0	9	3000	0	19.2 [152-50]	50.3 [395-80]
EGR Only,C100, (1800/1570Nm)	24.6	4.78	70	35.1	-5	30	2300	10.5 [145-121]	59.7 [200-62]	95.0 [465-95]
EGR Focused, B50	26.1	2.7	61	32.6	0	9	3000	0	21.7 [148-52]	35.6 [373-82]
EGR Focused, C100	28.1	4	55	24.9	-10	28	2200	14.8 [137-103]	53.7 [169-48]	58.5 [436-83]

condensing temperature of 40°C, an 8% fuel consumption improvement was calculated [6].

BCs are by no means the only technology for WHR. The development of thermo-electric generators for units under 1 kW has accelerated performance considerably over the last 5 years. Maximum module efficiency of 10% ($\Delta T=480^\circ\text{C}$) and 11% ($\Delta T=385^\circ\text{C}$) are reported by LaGrandeur et al. [7] and Schock et al. [8], respectively. Mechanical-Turbo-Compounding (MTC) is already established in HDDEs [9] and simulation results have shown BSFC improvements between 2.4% and 4% [6, 10]. Also, Electrical-Turbo-Compounding (ETC) is in demonstration phase and has been partially tested. The independent control of turbine and engine speed makes ETC more efficient compared to MTC, with BSFC improvements between 4% and 10% [11, 12]. However, the above studies show that BCs provides the largest BSFC improvement, they are less sensitive to vehicle load, and cost considerations (\$/kW) show them to be competitive [6, 13].

Efficiency of all the waste heat to power conversion technologies mentioned are limited by the flow rate and temperature levels of the heat streams. They face certain common interrelated barriers: payback periods, temperature limits of recovery equipment, thermal cycling, reliability, and performance. They will also include advanced controls to minimise the disadvantage linked to the varied driving conditions. Despite their success in stationary application, BCs face some technology specific barriers which are impeding their wider adoption and installation when applied to road transport application. These include: cost (economies of scale), chemical (corrosion/fouling, working fluid toxicity and flammability, potential of exhaust and working fluid mixing), physical (complexity, packaging, weight, crash safety) and performance (variable turbine/expander speed).

NO_x SOLUTION LAYOUTS

The advances in EGR, Diesel Particulate Filter (DPF), Turbo-Charger (T/C) and fuel injection equipment technology, have allowed the possibility to explore Euro 6 and US 2010 NO_x limits without after-treatment. The use of high EGR rate and the delayed combustion to meet Euro 6 engine-out NO_x emission avoid additional after-treatment but inherit the drawback of increasing engine BSFC. For US 2010 emissions it is estimated that an EGR only engine shows a 5-7% fuel penalty when compared to a Selective

Catalytic Reduction (SCR) focused platform [14]. However, when urea consumption is included the projected BSFC penalty for a SCR focused (Euro 4 engine out NO_x + 90% SCR) engine reduces to 4% for Euro 6 conditions [15].

The adoption of EGR only approach compromises on specific power output and fuel economy. With elevated boost, incylinder and rail pressures, a stronger mechanical design of the engine will be required. Mixing of EGR and Charge Air Cooler (CAC) stream, protection against fouling/corrosion and avoiding DPF filter plugging, all have to be ensured. To reduce start of combustion temperatures, considerable amount of waste heat has to be rejected from the inter-cooler and aftercooler. Furthermore, the increased exhaust gases cooled and diverted back to the intake will increase the complexity, volume, weight and cost of the engine's cooling module. However, there are some advantages of an EGR only engine when compared to a combined platform, including no urea requirement, lower operating cost, less maintenance and lower vehicle weight [16]. The estimated weight and cost for an additional low temperature EGR cooler, which will cool the EGR to 100°C is estimated to be only around 18 kg and \$750 respectively (on top of the standard EGR cooler) [6]. The after-treatment package (DPF+EGR+SCR) represents a cost of around \$17,100 for US 2010 emissions, which is not far below the cost of an HDDE engine [17], signifies the importance of exploring cost effective integrated solutions.

To investigate this, the addition of WHR on an EGR only engine was conducted by a simulation study. Also included are results for an EGR focused (Euro 5 engine out NO_x + 80% SCR) engine. To generate waste heat quantities and qualities typical of long haul engine, two 10L (EGR only and EGR focused) engine simulation models were developed in Ricardo WAVE 8.1 [18] running with the available test data from an experimental 2L single cylinder, Ricardo Proteus, HDDE [19]. The 2L engine is configured as a direct injection Diesel engine with a low swirl. A common rail single injection fuelling equipment with injection pressures up to 3000 bar was employed to partly compensate for the increase in particulate matter emission. As the exhaust temperature profoundly influence the WHR, the high temperatures along the exhaust line for the 10L models were matched within 20°C of the experimental values. The applied NO_x strategy for the two 10L engine platforms at a typical cruise (B50) and high load (C100) conditions along with the heat available in CAC and EGR heat exchangers with hot and cold temperatures are given in [table 1](#).



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METHODOLOGY

The temperature levels seen in the EGR cooler (370-470°C, [table 1](#)), cannot be simultaneously used to maximise engine BSFC while providing highly cooled EGR temperatures using the conventional superheated Rankine cycle method. This is due to water's largest ratio of latent heat to sensible heat. In this context, research on how to convert this temperature level heat source efficiently into power is of great significance. Organic and synthetic fluids can be selected with the necessary trade-offs between, thermodynamic, thermophysical, chemical, environmental, and safety properties to maximise the power conversion with an economically viable system.

A detailed selection study to identify potential working fluids for EGR WHR has already been conducted by the authors [20]. With multiple fluid screening criteria, common BC boundary conditions, and similar equipment performance assumptions, the study highlighted the system and performance benefits when using non-ozone depleting chlorinated fluids (R1130 and R30), acetone and ethyl iodide. When benchmarked for fixed evaporator pressures the selected fluids also showed advantages over R245fa, ethanol and water, the preferred options for automotive application in present literature.

Due to limitations associated with the EGR quality, quantity, and variability the influence of the selected working fluid and the corresponding operating condition can be vital. However, detailed studies on the selected operating condition and tradeoffs compared to the wide range of other operating modes are rarely published. Most of the investigations mentioned in the introduction section have been focused using recuperated ORC configuration, this ignores the overall conversion efficiency advantages that can be gained by exploring different operating modes with appropriate working fluids. There is still a great deal to learn about improving the performance and bringing down the costs for BC units for automotive application. To address this, the paper discusses extensive analyses and comparisons among different BC working conditions using pure fluids. The closed loop, single expansion derivative of the traditional BC is conducted to obtain conclusions in theory, with the results providing directions for practical implementation of BC units. To detail the influence of turbine inlet pressure, temperature, and vapour fraction on the BC performance and system, simulations were conducted at C100 quality and quantity values for the EGR only engine with the above seven fluids using Aspen HYSYS V7.3 software package [21]. The boundary conditions and assumptions used for BC simulations are detailed in [table 2](#).

BC parameters present a multi-dimensional surface on which an optimum condition can be found within prescribed constraints. The work described in this paper uses overall conversion efficiency (product of thermal and heat recovery)

as the objective function. The main objective of this study is focused on optimisation of turbine/expander inlet conditions to find the combination of working fluid and cycle operating condition that could show the best performance and system (size and cost) trade-off to achieve a better integration within a HDDE.

Table 2. BC equipment performance and boundary conditions used for simulations.

Cooled EGR temperature = 96-100 °C
Maximum cycle pressure = 65 bars
All heat exchanger pinch point = 30 °C
ΔP , exhaust side = 0.05 bar/heat exchanger
ΔP , working fluid side = 0.15 bar/heat exchanger
Turbine/expander efficiency = 75%
Pump efficiency = 65%
Condensing temperature = 65°C

WORKING FLUIDS AND CYCLE OPERATING CONDITIONS

The thermodynamic properties of a fluid are interrelated and largely dependent on critical point properties, normal boiling point, molecular makeup and structure [22]. [Table 3](#) covers thirteen necessary properties of the seven fluids used in this study. Within organic fluids it is observed that the ratio of normal boiling point at atmospheric pressure to critical temperature (i.e. reduced temperature) is in the range of 0.6-0.7. They show an approximate behaviour between the reduced vapour pressure and the corresponding reduced saturation temperature i.e., organic fluids with a lower boiling points have a higher vapour pressure at normal condensing temperatures and vice versa. A significant variable that affects the fluid applicability and the arrangement of associated equipment is its saturation vapour curve. [Figure 1a](#) and [1b](#) show the temperature-entropy diagram of the fluids used by other authors and the fluids proposed in this study, respectively. The saturated vapour curve is shown to be roughly dependent on molecular weight or molecular complexity (number of atoms in the molecule) of the substance. With increase in the number of bonded atoms, the molar heat capacity, and consequently the slope of the saturation boundary has been shown to increase. With pressures slightly below critical pressure, the working fluids can be divided according to the slope of their vapour saturation curve (dT/dS). Fluids like water, ethanol and R30 for which the entropy of the saturated vapour decreases with increasing temperatures are called wet fluids ($dT/dS < 0$). Wet fluids require superheating in order to avoid the formation of liquid droplets which may cause blade erosion at the turbine exit. Although, it is possible to expand dry saturated vapour using special materials for leading edges to allow some wetness ($\approx 10\%$) at exit, this sacrifices the turbine efficiency. Fluids like R245fa ([figure 1a](#)) where the entropy of the saturated vapour increases with increasing temperature are called dry fluids ($dT/dS > 0$). During expansion, they do not condense since the degree of superheat increases as

Table 3. Thermodynamic/thermo-physical and environmental/safety properties of the seven fluids discussed.

	Critical temperature T_c °C	Critical pressure P_c bar	Atmospheric boiling point T_b °C	Molecular mass M g/mol	Atmospheric liquid density ρ kg/m ³	Freezing point T_f °C	Vapour slope (wet/dry/isentropic) W/D/I	Atmospheric life time ATM yr.	Ozone Depletion Potential ODP	Global Warming Potential GWP	NFPA Health hazard H	NFPA Flammability hazard F	Auto ignition temperature T_{ign} °C
Water	373.9	220.6	100.0	18.0	998.1	0	W	<.019	0	0	0	0	
Ethyl-Iodide	280.9	47.1	72.5	156.0	1922.9	-111.1	I		0		2	2	
Trans-1,2-Dichloroethylene (R1130)	243.4	55.1	47.7	96.9	1248.7	-49.8	I	0.0348	0.00024	25	2	3	460
Ethanol	240.9	61.4	78.3	46.1	791.9	-114.1	W		0		2	3	363
Dichloromethane (R30)	236.9	60.8	39.8	84.9	1318.2	-95.1	W	0.394	<.001	10	2	1	556
Acetone	235.1	47.0	56.3	58.1	784.9	-94.7	I		0		1	3	465
R245fa	154.1	36.4	15.3	134.0	1364.4		D	7.6	0	1030	2	0	412

expansion takes place. However, if the fluid is too dry, the expanded vapour will exit with substantial superheat, increasing the condenser load. An ideal fluid would be one that would neither require superheating (wet) or de-superheating (dry), as large heat exchanger surface area are required for vapour heat transfer. The third classification, organic molecules with 5-10 atoms, are called isentropic fluids, with near quasi-vertical saturated vapour curves ($dT/dS \approx \infty$) they includes fluids like acetone, R1130 and ethyl iodide (figure 1b).

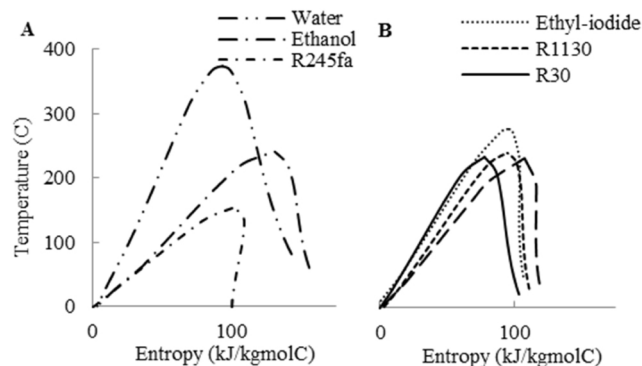


Figure 1. Temperature-entropy diagram of the seven fluids, (a) mentioned in published automotive literature, (b) proposed alternatives used in this study.

The expansion/power generation unit is a critical component of the BC hardware. The two widely proposed solutions for automotive application include either the use of a high speed turbine-generator unit for electrical output, or the use of a positive displacement expander coupled to the drive shaft for mechanical output. For a high speed turbine-generator unit various turbine technologies can be adapted from the stationary BCs. These include: axial flow turbines, radial inflow turbines, radial outflow turbine, variable phase turbines etc [23]. For automotive WHR, Cummins had selected a high speed (50,000 rpm) fixed-nozzle, axial inflow turbine generator with maximum working fluid temperature of 260°C [1]. Positive displacement type expanders (scroll, screw, reciprocating etc.) have speeds roughly one order of

magnitude less than those of turbines and permit some condensation during the expansion. For two-phase expansion, screw expanders have recently been proposed [24]. However, scroll and screw expanders usually have expansion pressure ratios below 8:1. For HDDEs the reciprocating expander is being considered as a valid alternative as they work even at high expansion ratios. The wide variety of turbine and positive displacement expanders along with high EGR temperatures has made it possible to consider the start the working fluid expansion from saturated vapour, superheated vapour, supercritical, and even saturated liquid or two phase mixtures. When considering turbine/expander inlet temperature, pressure, and vapour fraction a total of twelve BC operating conditions exists with pure dry, wet and isentropic fluids as detailed in figure 2a, 2b and 2c.

RESULTS AND DISCUSSION

Dry Saturated Subcritical Cycles

To examine the effect of turbine inlet parameters on BC performance, simulations were conducted for varying turbine inlet pressures and temperatures using the seven fluids. Figure 3a shows the variation in the first law efficiency with increasing turbine inlet pressures for EGR WHR. The cycle operating conditions were that of saturated dry expansion for dry fluids (figure 2c) and minimum superheat expansion for wet fluids (figure 2a). Figure 3a demonstrates that the first law efficiency increases with the increment in the turbine inlet pressure. The results are consistent for all the fluids, with fluids with a high boiling point being more efficient. This can be understood with reference to figure 4a which refers to ethyl iodide, where by increasing the evaporator pressure from 20 bar to 45 bar, the temperature difference between the working fluid and the EGR stream reduces. This results in greater cycle area and hence improved efficiencies. Also, from figure 3a, it can be seen that the rate of efficiency improvement reduces with the increasing maximum pressure. Working fluids show maximum values while approaching their respective critical point conditions (given in table 2).