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Crank angle-resolved exergy analysis of exhaust flows in a diesel engine from the perspective of exhaust waste energy recovery

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HIGHLIGHTS

- First characterization of crank angle-resolved exhaust exergy flow in diesel engine.
- Mass-specific and cumulative exhaust exergy results are presented.
- Thermal and mechanical exhaust exergy components are quantified for exhaust WER.
- Exergy apportionment in blowdown and displacement phases characterized.

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ABSTRACT

Exhaust waste energy recovery (WER) is a critical component in the portfolio of efficiency improvement strategies being considered for internal combustion engines. This paper addresses an important existing knowledge gap by introducing a methodology for performing crank angle-resolved exergy analysis of exhaust flows from the perspective of exhaust WER in diesel engines. To this end, a single-cylinder research engine (SCRE) operating in conventional diesel combustion mode was tested at a load of 5 bar brake mean effective pressure (BMEP), speeds of 1200 and 1500 rpm, and boost pressures of 1.2, 1.5, 2, and 2.4 bar. The crank angle-resolved specific exergy and its thermal and mechanical components were calculated by combining experimental crank angle-resolved exhaust manifold pressure measurements with 1D system-level (GT-POWER) simulations. In addition, exhaust flow specific exergies in the "blowdown" and "displacement" phases of the exhaust process, the total exergy flow rates, and cumulative (time-integrated) exergy were quantified. The results obtained show that low boost pressures led to the highest crank angle-resolved specific exergy, the lowest specific mechanical exergy, and the highest specific thermal exergy. In general, the specific thermal exergy was dominant during the initial phase of the exhaust process while the specific mechanical exergy became important after peak mass flow rate was attained. Regardless of engine speed, with increasing boost pressure, the mechanical component of the cumulative exergy in the exhaust flow increased while the thermal component decreased. Consequently, the results indicate that highly boosted conditions may be more appropriate for direct WER with positive displacement expanders that leverage the mechanical component of exhaust exergy while low boost operating conditions may be better suited for other WER strategies that utilize the thermal component of exhaust exergy.

1. Introduction and the need for crank angle-resolved exhaust exergy flow analysis

Increasing the fuel conversion efficiency (FCE) of internal combustion (IC) engines continues to be one of the primary challenges faced by engine designers. In particular, the heavy-duty trucking industry is faced with a new paradigm of demonstrating engine technologies to achieve 55% brake thermal efficiency (BTE) for future heavy-duty diesel engine (HDDE) trucks under the aegis of the US Department of Energy's ongoing SuperTruck II program. Among the in-cylinder strategies being considered to enable high BTE engine operation are rapid combustion, extremely high-pressure fuel injection (greater than 3000 bar) with rate shaping, adoption of Atkinson cycle operation, and various advanced low temperature combustion strategies such as gasoline compression ignition (GCI) [1], homogeneous charge compression ignition (HCCI) [2,3], partially premixed combustion (PPC) [4,5],

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Nomenclature

Abbreviations

BDC	Bottom Dead Center
BMEP	Brake Mean Effective Pressure [bar]
BTE	Brake Thermal Efficiency
CAD	Crank Angle Degree
CI	Compression Ignition
CO_2	Carbon Dioxide
DAQ	Data Acquisition
DEP	Divided Exhaust Period
EGR	Exhaust Gas Recirculation
EVC	Exhaust Valve closing [CAD]
EVO	Exhaust Valve Opening [CAD]
IC	Internal Combustion
FCE	Fuel Conversion Efficiency [%]
GCI	Gasoline Compression Ignition
HCCI	Homogeneous Charge Compression Ignition
HDDE	Heavy Duty Diesel Engine
IMEP	Indicated Mean Effective Pressure [bar]
IVC	Intake Valve Closure [CAD]
IVO	Intake Valve Opening [CAD]
LTC	Low Temperature Combustion
NO_x	Nitrogen Oxides
ORC	Organic Rankine Cycle
PPC	Partially Premixed Combustion
rpm	revolution per minute
SADI	Stand Alone Direct Injector Driver
SCRE	Single Cylinder Research Engine
SI	Spark Ignition
TDC	Top Dead Center
TPA	Three Pressure Analysis
VEMB	Valve Event Modulated Boost
VI	Virtual Instrument
WER	Waste Energy Recovery

Subscripts

B	blowdown
CH	chemical
D	displacement
in	input
KN	kinetic
ME	mechanical
PH	physical
PT	potential
TH	thermal
ss	steady state
0	dead state

and dual fuel low temperature combustion [6,7]. However, it is widely accepted that it would be very difficult to demonstrate 55% BTE on HDDEs with only conventional crank angle-resolved in-cylinder performance improvement strategies, i.e., without exhaust waste energy recovery (WER). Despite this critical need for exhaust WER, current engine exhaust WER strategies that utilize organic Rankine cycles (ORCs) face the daunting challenge of reducing the high cost per unit power output ($/kW), which adversely affects both their overall economic feasibility and widespread adoption. A possible alternative might be low-cost direct WER systems that can take advantage of the pressure pulse during the crank angle-resolved "blowdown" phase of exhaust flows to recover pressure energy that is usually irrecoverably lost. The current engine WER literature does not specifically address the amount of available work (exergy) in the exhaust flow during the crank angle-resolved blowdown and "displacement" phases of the exhaust process. Also, no results are currently available for providing engine WER designers with reasonable estimates of the proportion of crank angle-resolved mechanical exergy (i.e., due to higher-than-ambient dynamic exhaust pressures) and thermal exergy (i.e., due to higher-than-ambient exhaust temperatures) available in engine exhaust flows. For this purpose, the present work examines crank angle-resolved exhaust exergy in a diesel engine from the perspective of WER. The goal of the present paper is not to improve the performance of the engine itself but to provide an analytical framework for determining the type of exhaust WER system that may be beneficial under different engine operating conditions based on the crank angle-resolved exhaust exergy flow characteristics. The paper is structured as follows. First, a detailed literature review is performed to present the state-of-the-art regarding exhaust WER techniques. This is followed by a discussion of the objectives of the present work, the analysis methodology, the experimental setup, and the system-level simulations (performed using GT-POWER). Finally, the crank angle-resolved exhaust exergy results are presented along with a discussion of their practical implications vis-à-vis exhaust WER.

2. Review of current exhaust WER strategies

As discussed above, efficiency improvement alternatives to conventional in-cylinder methodologies include WER. In this method, the FCE of the engine is increased by extracting work from otherwise wasted energy sources (e.g., exhaust, coolant, etc.) of the engine [8]. Considering that the average brake FCE lies in the range of 25–28% for SI engines and 34–38% for CI engines, the typical energy losses associated with the exhaust streams are of the order of 36–50% for SI engines and 23–37% for CI engines and the coolant heat transfer losses are about 17–26% for SI engines and 16–35% for CI engines [9]. Distribution of input fuel energy in engines between brake work delivered, the heat transferred to the coolant, and the energy carried out of the cylinders with the exhaust gas has been studied in previous research efforts [10–12]. For example, Ozkan et al. [10] showed a slight increase in the intercooling and exhaust losses when using pre injection strategies on a diesel engine. Li et al. [11] investigated the distribution of input energy at different engine coolant temperatures in a conventional light duty diesel engine. Based on experimental and simulation results, they found that about one-third of the input fuel energy is rejected to the exhaust gas while more than 40% is converted to net indicated work and the rest is transferred as heat through the chamber walls and to the lubricating oil. They reported that by increasing the engine coolant temperature the exhaust losses increase while simultaneously causing an equivalent reduction in cylinder heat transfer. Singh et al. [12] studied the various energy losses of a passenger car diesel engine at different engine operating conditions and observed a significant change in energy balance with increasing the coolant temperature from 40 °C to 80 °C. This resulted in a reduction in coolant heat transfer, an increase in brake power and exhaust loss, and an increased potential to increase the powertrain efficiency by utilizing an exhaust waste energy recovery system.

These energy loss distributions indicate a tremendous potential for increasing the FCE of both SI and CI engines by employing WER strategies. In particular, since the temperatures and pressures of the exhaust streams in both SI and CI engines are substantially higher than the corresponding coolant temperatures, the energy content of the exhaust streams is higher compared to that of the coolant streams. Consequently, many contemporary WER technologies have focused on tapping the energy in the exhaust streams.

The WER technologies can be classified as direct or indirect