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Simulation of a heavy-duty diesel engine with electrical turbocompounding system using operating charts for turbocharger components and power turbine

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ABSTRACT

In diesel engines, approximately 30–40% of the energy supplied by the fuel is rejected to the ambience through exhaust gases. Therefore, there is a potentiality for further considerable increase of diesel engine efficiency with the utilization of exhaust gas heat and its conversion to mechanical or electrical energy. In the present study, the operational behavior of a heavy-duty (HD) diesel truck engine equipped with an electric turbocompounding system is examined on a theoretical basis. The electrical turbocompounding configuration comprised of a power turbine coupled to an electric generator, which is installed downstream to the turbocharger (T/C) turbine. A diesel engine simulation model has been developed using operating charts for both turbocharger and power turbine. A method for introducing the operating charts into the engine model is described thoroughly. A parametric analysis is conducted with the developed simulation tool, where the varying parameter is the rotational speed of power turbine shaft. In this study, the interaction between the power turbine and the turbocharged diesel engine is examined in detail. The effect of power turbine speed on T/C components efficiencies, power turbine efficiency, exhaust pressure and temperature, engine boost pressure and air to fuel ratio is evaluated. In addition, theoretical results for the potential impact of electrical turbocompounding on the generated electric power, net engine power and relative improvement of brake specific fuel consumption (bsfc) are provided. The critical evaluation of the theoretical findings led to the basic conclusion that there is a significant potential for bsfc improvement of HD diesel truck engines with the proposed electrical turbocompounding concept, which reaches up to 4% at full engine load. The improvement of bsfc with electric turbocompounding appears to be more attractive solution in terms of technical complexity and installation cost against other competitive heat recovery technologies such as Rankine cycle systems.

1. Introduction

Diminishing petroleum supplies and increasing fuel cost have motivated diesel engine manufacturers and engineers to improve fuel economy. During recent years, various in-cylinder technologies have been implemented to increase further diesel engine efficiency and thus, to curtail CO_2 emissions and simultaneously to reduce further diesel-emitted gaseous and particulate pollutants [1,2]. During the last decade, the in-cylinder measures used to improve conventional diesel engine efficiency and polluting behavior have been primarily focused on the manipulation of fuel injection process (i.e. increase of fuel injection pressure, variation of fuel injection timing and rate and application of multiple injection events) and on the development and implementation of advanced turbocharging systems [3–6]. Towards a further improvement of the operational and environmental behavior of diesel engines, alternative low temperature combustion (LTC) strategies such as Homogeneous Charge Compression Ignition (HCCI), Premixed Charge Compression Ignition (PCCI) and Reactivity Controlled Compression Ignition (RCCI) have been examined both theoretically and experimentally during recent years [1,2]. The application of the aforementioned LTC techniques in diesel engine generated quite promising results mainly in the field of simultaneous reduction of soot and NOx emissions, which are the pollutants of primary interest in diesel engines.

However, the application of the aforementioned in-cylinder measures and advanced LTC technologies has not succeeded in providing remarkable improvements of diesel engine brake efficiency. For this reason, during recent years, research community has been intensively focused on the improvement of diesel cycle management. According to diesel cycle principles, a significant

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Nomenclature

$\dot{m}$	flow rate (kg/s)
$\dot{N}$	rotational speed (r/min)
A	area (m^2)
a_{del}	ignition delay constant
C_0	mass fraction of oxygen
c_d	discharge coefficient
C_f	mass fraction of fuel
c_p	constant pressure thermal heat capacity (J/kg K)
d_{inj}	injector hole diameter (m)
E	activation energy (J/kmol)
$EFF_{T/C}$	turbocharger efficiency
h	heat transfer coefficient (W/m^2 K)
K_b	combustion rate constant
l_{car}	characteristic length (m)
m	mass (kg)
n_{compr}	compressor isentropic efficiency
n_{mTC}	turbocharger isentropic efficiency
p	pressure (bar)
Power	power (W)
$Power_{frTC}$	frictional power loss in turbocharger shaft (W)
Pr	Prandtl number
Re	Reynolds number
R_{mol}	universal gas constant (J/kmolK)
S_{pr}	ignition delay integral
T	temperature (K)
t	time (s)
t_b	break up time (s)
t_{hit}	time of impingement (s)
u	velocity (m/s)
u_p	penetration velocity (m/s)

Greek symbols

γ	Isentropic exponent
Δp	pressure difference (Pa)
ε_t	viscous dissipation rate per unit mass (W/kg)
η	efficiency
λ	thermal conductivity (W/m K)
ρ	density (kg/m^3)
Φ_{eq}	equivalence ratio

Subscripts

air	air
compr	compressor
COR	corrected value
del	delay
ET	electrical turbocompounding
f	fuel
g	gas
GEN	generated
in	inlet
inj	injection
l	liquid fuel
p	penetration
ST	standard engine operation
TC	turbocharger
turb	turbine

Abbreviations

ATDC	after top dead center
bmep	brake mean effective pressure
bsfc	brake specific fuel consumption
CA	crank angle
CAC	charge air cooler
EGR	exhaust gas recirculation
HCCI	homogeneous charge compression ignition
HD	heavy duty
LTC	low temperature combustion
NOx	nitrogen oxides
ORC	organic Rankine cycle
PCCI	premixed charge compression ignition
RCCI	reactivity controlled compression ignition
SRC	steam Rankine cycle
T/C	turbocharger, turbocharged
TEG	thermoelectric generator
WHR	waste heat recovery

amount of fuel supplied energy is not transformed into useful mechanical power and it is rejected to the ambience as exhaust heat. In existing diesel engines, the unexploited waste heat reaches up to 30–40% of the feeding fuel energy. Hence, potentiality for significant improvement of diesel engine efficiency is envisaged through the utilization of exhaust energy for additional power generation.

Recent review studies [7–11] examined thoroughly the implementation of various waste heat recovery (WHR) technologies on both theoretical and experimental basis and demonstrated the individual impact of each technology on the improvement of brake specific fuel consumption (bsfc) and on the operability of modern diesel engines under steady-state and transient operation. The aforesaid WHR strategies can be effectively implemented in various applications of diesel engines such as transportation vehicles, marine propulsion and electric power generation [11–15]. Especially, in the field of heavy-duty (HD) diesel engines, which are used as prime movers of trucks, the dominating WHR technologies are the following:

1.1. Mechanical turbocompounding

This WHR technology involves the installation of a power turbine after the turbocharger (T/C) turbine for extracting mechanical power from the exhaust gas stream. Studies conducted in the past mainly by engine manufacturers have shown that the implementation of mechanical turbocompounding in HD diesel engines may result in considerable bsfc improvement [16–23]. Specifically, Leising et al. [16] examined the installation of an axial power turbine downstream to the T/C turbine of a 14.6-L diesel engine and they reported an average bsfc reduction of about 4.7% for a 50,000 miles extra-urban driving test in the US. Tennant and Walsham [19] implemented mechanical turbocompounding on an 11-L 6-cylinder T/C diesel engine and they reported a 5% bsfc improvement at full load.

1.2. Electrical turbocompounding

The concept of this strategy is based on the coupling of an electrical generator to the T/C shaft for extracting excess power produced from the turbine. In this case, the turbine produces more power compared to the one required to drive the compressor. The excess power is converted to electric power using a high speed generator incorporated into the T/C casing. Earlier studies performed on the field of electrical turbocompounding have demonstrated that the application of this WHR technology in HD diesel engines may achieve comparable or higher bsfc reductions compared to the aforementioned mechanical turbocompounding