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The effects of steam injection on the performance and emission parameters of a Miller cycle diesel engine

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ABSTRACT

The application of the Miller cycle into the internal combustion engines is proposed to decrease NOx emissions, in the recent years. Another NOx control technique is the steam injection method (SIM). In this study, the application of these methods together into a single cylinder, direct injection diesel engine is experimentally and theoretically performed. Two different Miller cycles, which provide 5 and 10 crank angle (CA) retarding compared to standard condition, are applied with two different camshafts. SIM is applied at three different injection rates which are 10%, 20% and 30% of the fuel mass. The results obtained are compared with standard conditions in terms of the performance and emissions. The simulation results are verified with experimental data with non-notable errors. In the experimental results, NO and CO_2 emissions decreased up to 48% and 2.2%; HC and CO emissions increased by 46% and 34% with the penalty by 6.4% and 9.2% for the effective power and efficiency. The optimum condition has been defined as 10 CA retarding and 30% steam injection rate (C62-S30) in terms of the maximum NO reduction. The results demonstrate that the combination can be applied into the diesel engines to minimize NO and CO_2 emissions.

1. Introduction

In the recent years, the application of the Miller cycle into the internal combustion engines has been become widespread in the engine researchers. This method provides a high decrease rate in the formation of NOx emissions [1–9]. Another technique is the SIM (steam injection method) which has been recently developed to decrease NOx emissions released from internal combustion engines [19–22]. In order to obtain maximum NOx reduction rate, the combination of these two methods may be used in the diesel engines.

Wang et al. [1] experimentally reduced NOx emissions by applying the Miller cycle into a diesel engine. Wang et al. [2,3] carried out an experimental [2] and an analytical [3] study on the Miller Cycle Otto Engine with late intake valve closing version in order to decrease NOx emissions from a petrol engine. Miller cycle decreased the compression pressure and temperature in the cylinder at the end of compression stroke. Thus, lower exhaust temperature and less NOx formation were seen compared to those of standard Otto cycle.

Mikalsen et al. [4] investigated the feasibility and potential advantages of the application of the Miller cycle into a small scale Otto cycle natural gas engine by using multidimensional simulation for a combined heat and power system. As a result, the SFC (specific fuel consumption) of the engine was reduced with the cost of a decreased power to weight ratio. Gonca et al. [5–8] computationally demonstrated that the application of Miller cycle into a diesel engine could abate the NO emissions and increase the effective efficiency. Sarkhi et al. [9–11] investigated the effects of the variable specific heats of the working fluid on the performance for an air standard reversible Miller cycle [9] and irreversible Miller cycle [10]. In another study, Sarkhi et al. [11] analyzed the cycle performance by using the maximum power density criteria. Zhao and Chen [12] conducted a performance analysis for an-air standard irreversible Miller cycle with respect to the change of the pressure ratios. Ebrahimi [13] analyzed an air standard reversible Miller cycle with respect to variation of engine speed and variable specific heat ratio of working fluid and Ebrahimi [14] analyzed an air

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Nomenclature

A	heat transfer area (cm^2)
C_v	constant volume specific heat (kJ/kg K)
C_p	constant pressure specific heat (kJ/kg K)
C	blow by coefficient
B	bore (cm)
F	fuel–air ratio
h	specific enthalpy (kJ/kg)
h_{tr}	heat transfer coefficient (W/m^{2}K) of burnt and unburnt zones
H	enthalpy (kJ/kg)
H_u	low heat value of the fuel (kJ/kg)
m	mass (g)
$\dot{m}$	time-dependent mass rate (g/s)
M	molecular weight (g)
n	injection constant
P	pressure (bar)
Q	loss heat passed through the cylinder wall (J)
$\dot{Q}$	rate of heat transfer (J/s)
RGF	residual gas fraction
s	specific entropy (kJ/kg K)
S	stroke (cm)
T	temperature (K)
u	specific internal energy (kJ/kg)
v	specific volume (cm^3/g)
V	volume (cm^3)
W	work output (J)
x	burn fraction
$\dot{x}_i$	fraction rate of the total injected fuel mass

Greek letters

ε	ratio of half stroke to rod length
ϕ	equivalence ratio
$\Gamma(n)$	gamma function
θ	crank angle (degree)
τ	time (ms)
ω	angular velocity (rad/s)

Subscripts

a	air
b	burned zone
cyl	cylinder
di	injection duration parameter
dif	diffusive combustion phase
f	fuel
fi	injected fuel
id	ignition delay(ms)
l	leak, loss
pre	premixed combustion phase
r	reference
si	start of fuel injection (degree)
st	stoichiometric
u	unburned zone
w	cylinder walls

standard irreversible Miller cycle with respect to the variation of relative air–fuel ratio and stroke length based on finite-time thermodynamics. The power output and thermal efficiency were obtained by introducing the compression ratio, air–fuel ratio and stroke length. It was illustrated that the power output and thermal efficiency of the cycle reach to maximum point with certain values of the compression ratio. Rinaldini et al. [15] carried out an experimental and numerical study by using KIVA which is a CFD based code. They assessed the potential and the limits of the Miller cycle application into a High Speed Direct Injection (HSDI) Diesel engine in terms of abating NOx and soot. It was shown in the results that when the Miller cycle is applied to a diesel engine, NOx and soot emissions could be reduced up to 25% and 60%, respectively. Li et al. [16] experimentally examined the effects of the Miller cycle with early and late intake valve closing (EIVC and LIVC) versions on the brake specific fuel consumption (BSFC) of a boosted direct injection (DI) gasoline engine. At the high load conditions, the fuel economy is improved up to 4.7% with LIVC; however, a considerable change was not seen in SFC with EIVC version. At the low load conditions, SFC is improved up to 6.8% and 7.4% with LIVC and EIVC versions, respectively. Wu et al. [17] studied on the analysis of a supercharged Miller cycle Otto engine with EIVC version. Ge et al. [18] examined the influences of heat transfer and friction losses on the performance of an air standard Miller cycle based on finite-time thermodynamics.

The steam injected method firstly was proposed by Parlak et al. [19]. This method yielded lower NOx emissions by 33% compared to standard condition for a single cylinder, naturally aspirated diesel engine. Also, the engine performance increased up to 3%. Kokkulunk et al. [20,33] investigated the effects of steam injection and EGR applications on the engine performance and NO emission of a direct injection diesel engine. Gonca et al. [5,6] conducted a theoretical study to compare the steam injected diesel engine and the Miller cycle diesel engine using two-zone combustion model. It was observed from the results that the Miller cycle and steam injection decrease the NO emissions at high rates. Cesur et al. [21] and Kokkulunk et al. [22] applied steam injection method into gasoline and diesel engines; they observed a reduction in NOx emissions and a increment in engine performance. Gonca et al. [23] studied on determination of the optimum steam temperatures and optimum steam mass ratios for turbocharged internal combustion engines.

Gonca [24] applied the SIM into a diesel engine fueled with the diesel–ethanol blend. The results showed that the method could improve the engine performance and decrease NO emissions. Parlak et al. [25] investigated the influences of the steam injection on a diesel engine fueled with tobacco seed oil methyl ester.

In this study, the influences of the application of the Miller cycle and steam injection on the performance and emission outputs for a naturally aspirated direct injection single cylinder diesel engine have been examined experimentally and theoretically. Engine torque, effective power, effective efficiency, SFC and the NO, CO, CO$_2$ and HC emissions have been experimentally obtained. The experimental results have been compared with the results of two-zone combustion model and a good approximation has been obtained with non-prominent errors. There is no study like this including the application of the Miller cycle and steam injection together, in the literature. Apart from former studies in the literature, this study also includes a comprehensive comparison of theoretical and experimental results for a steam injected and Miller cycle diesel engine.

2. Materials and method

2.1. Experimental set-up

The experiments were performed with a single cylinder, four-stroke and direct injection (DI) diesel engine. Table 1 demonstrates the engine properties. The Miller cycles are provided by retarding the closing of intake valve as 5 and 10 CA (crank angle). The original