Novel thermal throttling model in spark ignition engines: A way to replace a mechanical one

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ABSTRACT

Enhancing vehicles performance is one of the pivotal themes that has received considerable attention recently. Thermal throttling is considered as one of the rising techniques to boost engine volumetric efficiency. Therefore, the present study aims to develop a novel numerical model of a thermal throttling engine to address its features through holding a comparison against the conventional mechanical throttling. The main concept lies in replacing the mechanical throttling with a heat exchanger to control the quantity of the fresh charge by raising its temperature instead of decreasing its pressure. The model is applied on Mercedes Benz 250se SI engine run with natural gas fuel and validated towards experimental results. Furthermore, a full design and performance analysis are carried out to the heat exchanger (plate type) used in the proposed model. The results reveal a promising performance compared to the mechanical throttling, especially at part-load, with a drop in brake specific fuel consumption by 90 gm/kWh, an enhancement in volumetric efficiency by 40% and an increase in thermal efficiency by 12%. Moreover, the most efficient approach of controlling the outlet intake air temperature in the heat exchanger is by adjusting exhaust mass flowrate instead of intake mass flowrate.

1. Introduction

Many attempts are being followed up in pursuit of enhancing the vehicle performance. Thus, the light is shed on engine, which is a substantial unit in vehicles, through boosting the engine volumetric efficiency. Many approaches and manners are developed to refine and improve the volumetric efficiency: using turbo charger [1–4], super charger [1], intake manifold length [5,6], variable valve timing [7,8], fuel injection location (port fuel injection [9,10] or direct injection SI engine [11,12] and either throttle-less engines or lean burn engines [2,13–15]. Among these techniques, thermal throttling/throttleless premixed charge approach has promising potentials in terms of fuel efficacy and emissions for urban mass transit and goods delivery vehicles.

By implementing thermal throttling approach, the engine turns into a throttleless engine or lean-burn engine, where the throttle valve is replaced by a heat exchanger to control the amount of air/fuel mixture needed to be burned with respect to load. The primary function of heat exchanger is to adjust and manipulate the intake mixture temperature, thereby changing the mixture density and mass flow rate [2,13–15]. The heat is exchanged between exhaust gases, taking the advantage of its high temperature, and intake mixture so that the intake mixture temperature increases leading to less possibility of lean misfire and

leaner mixture, which could be used. In order to control the brake mean effective pressure (*bmep*), adjustment of mixture equivalence ratio along with mixture preheating is employed. In throttleless SI engine, Szwaja et al. [16] found that either double stage combustion technique or engine with pre-chamber witnesses a maximum thermal efficiency of 34% at excess air ratio (λ) of = 1.9 [17]. Moreover, for partial stratified combustion, Reynolds et al. [18] showed that, at λ = 1.65, there is a drop in brake specific fuel consumption of 20 gm/kWh compared to the traditional SI engine. Thermal throttling's results show an improvements over previous engines as at λ = 1.8, the thermal efficiency equal 37% and the brake specific fuel consumption equal 195 gm/kWh which lower than traditional SI engine by 100 gm/kWh [19].

In this sense, thermal throttling engines has numerous potential fuel efficiency and emissions advantages especially for urban mass transit and goods delivery vehicles since, usually, they are operated at respectively highly throttled conditions. Furthermore, thermal throttling concept provides all the features of premixed-charge and spark-ignition engines but with higher part-load thermal efficiency of no premixed-charge compression-ignition (Diesel-type) engines. This high part-load thermal efficiency is due to the lean operation without a pressure-reducing throttle, high power to weight ratio and relatively low NO_x and particulate matters emissions. Additionally, the cycle pumping losses in thermal throttling engines is eliminated and the lean misfire limit is

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Nomenclature

A_c	Intake valve seat area, m^2
A_{fch}	Channel flow area, m^2
bmep	Brake mean effective pressure, Pa
C_f	Flow coefficient
C_r	Heat capacity ratio
d_h	Hydraulic diameter, m
L_C	Length of heat exchanger, m
$\dot{m}$	Mass flow rate, kg/s
N_{ch}	Number of channels
N_p	Number of plates
NTU	Number of transfer units
Nu	Nusselt number
P_d	Pressure drop, Pa
P_{gap}	Gap Length, m
Pr	Prandtl number
Pw	Width length, m
Q	Heat transfer rate, W
Qmax	Maximum heat transfer rate, W
r	Compression ratio

R	Compression ratio
Re	Reynolds number
T_{ad}	Adiabatic temperature, K
T_{comb}	Combustion temperature, K
T_{eg}	Temperature of end gases, K
T_{in}	Intake air temperature, K
TPCE	Throttleless premixed charge engine
T_{ci}	Inlet air temperature, K
T_{hi}	Inlet exhaust temperature, K
T_{co}	Outlet air temperature, K
T_{ho}	Outlet exhaust temperature, K
V	Velocity, m/s

Greek letters

ϕ	Equivalence ratio
γ	Specific heat ratio
ε	Effectiveness
λ	Excess air ratio
ρ	Density, kg/m^3

broadened and henceforward the specific fuel consumption is improved. However, till now, a very limited literature was carried out to highlight the promising potentials of this technique because of the obstacles of its applicability that may come up when implementing it.

Therefore, the aim of the present work lies in proposing and implementing a novel model of a thermal throttling engine highlighting its features against the conventional mechanical throttling one. On that basis, in-depth numerical analysis was carried out to evaluate the proposed model performance, which was validated towards experimental results, compared to the mechanical one in terms of fuel consumption, volumetric efficiency and thermal efficiency. Furthermore, the heat exchanger used in the presented thermal throttling model is fully designed besides analyzing its performance towards various operating conditions of the engine.

2. Thermal throttling model description

The intake manifold in the thermal throttle engine proposed is divided into two branches; preheated stream branch and non-preheated stream branch. The amount of preheat stream can be controlled through adjusting a diverter valve in the intake manifold. The heated air mixes with fuel and, then, flows into the combustion chamber as shown in Fig. 1.

At Part load operating condition, brake mean effective pressure (*bmep*) is controlled by varying both equivalence ratio (ϕ) and intake air temperature (T_{in}). For each intake air temperature, the drop in equivalence ratio results in a reduction in the brake mean effective pressure. It is noted that, at the beginning, the reduction in *bmep* is almost linear since the heat input is nearly linear with ϕ. For further drop in ϕ, the decrease become steeper as an indication to the lean misfire limit approach. At higher T_{in}, the maximum *bmep* is lower because mixture density and ϕ value are less, where the curves begin to steepen. The outer envelope of these points represents combinations of ϕ and T_{in} providing the best thermal efficiency for a given *bmep*. These points, examples of which are identified by arrows, will be denoted "BEST TPCE" while all the other points will be donated "OTHER TPCE".
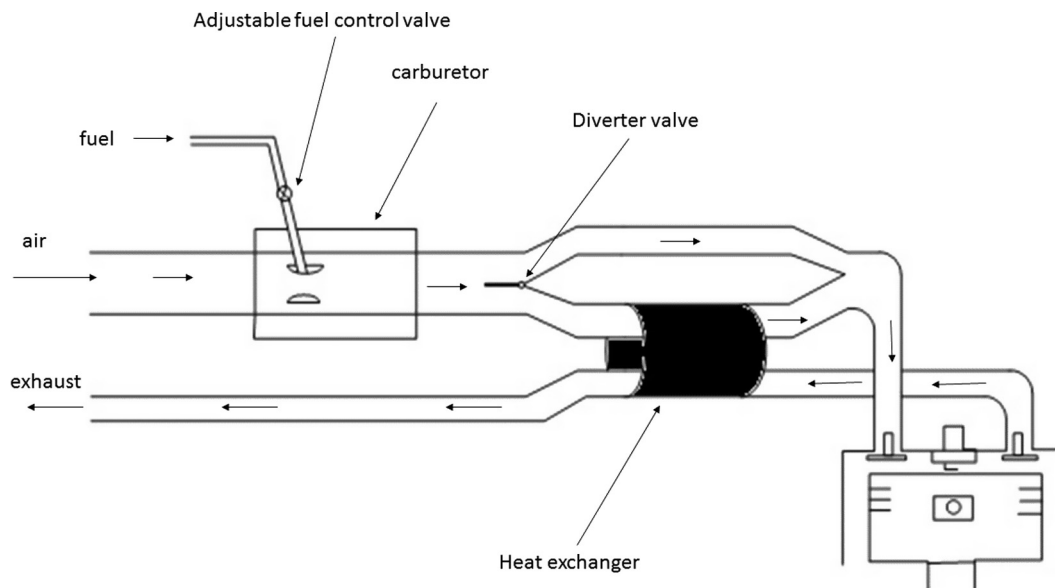

Fig. 1. Schematic of thermal throttling engine.