Performance and emission characteristics of the thermal barrier coated SI engine by adding argon inert gas to intake mixture

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ABSTRACT
Dilution of the intake air of the SI engine with the inert gases is one of the emission control techniques like exhaust gas recirculation, water injection into combustion chamber and cyclic variability, without scarifying power output and/or thermal efficiency (TE). This paper investigates the effects of using argon (Ar) gas to mitigate the spark ignition engine intake air to enhance the performance and cut down the emissions mainly nitrogen oxides. The input variables of this study include the compression ratio, stroke length, and engine speed and argon concentration. Output parameters like TE, volumetric efficiency, heat release rates, brake power, exhaust gas temperature and emissions of NOx, CO2 and CO were studied in a thermal barrier coated SI engine, under variable argon concentrations. Results of this study showed that the inclusion of Argon to the input air of the thermal barrier coated SI engine has significantly improved the emission characteristics and engine's performance within the range studied.

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Introduction
IC Engine has become an indispensible prime mover for use in transportation and agriculture sectors, because of this environmental protection from the toxic emissions of IC gained researchers interest. International emission regulations ratified in recent years have imposed more rigorous limits on engine emissions and fuel consumption.

Several New combustion techniques have been developed to meet the emission regulations, and to improve engine performance. Some of the techniques deal with the recirculation of the exhaust gasses to improve the combustion process, usage of fuel blends, varying stroke length and compression ratio, after treatment devices like catalytic converters to convert NOx and CO into non-toxic gasses before they released into atmosphere, injecting water into the combustion chamber of the engine [1].

Among SI engines emissions NOx are the most dangerous pollutants. Main oxides of N2 are NO and NO2. High combustion temperatures are responsible to the generation of NO and NO2. Many other oxides like N2O, N2O, N2O5, N2O3 are also formed in low concentration but they decompose spontaneously at ambient conditions of NO2. The maximum NOx levels are observed with A:F ratios of about 10% above
stoichiometric. Oxides of nitrogen and other obnoxious substances are produced in very small quantities and, in certain environments, can cause pollution, while prolonged exposure is dangerous to health.

Combustion duration plays a significant role in NOx formation within cylinder. NOx highly undesirable, because it reacts to the atmosphere to form ozone and causes photochemical smog. NOx is mostly created from nitrogen (N₂) of air. Sometimes the fuel contains nitrogen in compound form, for example NH₃, NC, HCN [2].

There are a number of NOx control technologies that have been developed for SI Engines such as modified combustion to suppress NOx formation; they are Low excess air operation, off-stoichiometric combustion and exhaust gas recirculation. Several exhaust gas treatment techniques are available, but they are costly.

The power gain and (or) TE have to be castigate with these methods. The promising approach to reduce NOx emissions form a SI engine is to replace a small percentage of N2 in the intake air with an inert gas. It was found that the CO₂ of the emissions in the EGR technique has only a small effect on the emissions as it is having low specific heat value [3].

In this study Argon gas having a specific heat ratio (Cₚ) of 1.6 at ambient temperature is considered to compensate the low Cₚ of the CO₂. It was considered that the Cₚ of added Ar and replaced N₂ are equal, why because as the specific heat ratio of the mixture increases the cylinder peak pressure also raises and it occurs at prior crank angles [4].

To reduce bsfc in cylinder heat rejection and to improve TE adopting higher compression ratios are a usual practice in IC engines. Increase in thermal and mechanical stresses is the result of both the cases. According to the second law of thermodynamics TE of an IC engines increases by insulating the Combustion chamber of the engine. Insulation of the engine combustion chamber enhances the durability of the engine at elevated temperatures [5].

Literature reviews reveal insulation of the engine combustion chamber reduces heat rejection, improves TE and increases energy availability in the exhaust. But some researchers reported that they observed no considerable improvement in TE [6,7]. Different composites like SiCa, silicon nitride, Al, MgSiO₂ and other ceramic materials were used in Low hear rejection engine concept [8].

Because of this, it is the main desire of the present study to probe in detail the effects of argon gas as an intake air diluting gas of the engine to analyze the performance and emissions. The present study was performed on a single cylinder, port fueled, 4 stroke SI engine whose pistons were coated with MgZrO₃ (with a thickness of a 320 µm) and NiCrAl (over a thickness of 160 µm) bond coat. CaZrO₃ was used to coat cylinder head and valves. The aim of the present work is to investigate the thermodynamics properties of the intake gas mixture with added Ar, the effects of inclusion of argon on the output parameters of the engine and on the emissions, and heat release rate.

**Experimental**

A four stroke engine with modified intake to admit the preset concentrations of argon and air (O₂ + N₂) was used. This section deals with the apparatus used for the experiments and its procedure.

**Engine experimental apparatus**

A mono cylinder port fuel, 4 stroke and water cooled SI engine coated with MgZrO₃ and NiCrAl was used in the present study. CaZrO₃ was coated for the cylinder head and valves of the engine in the present work. An engine having the facility to add Ar gas up to 15% of the intake air was used in the present work. The test rig built has the capability to vary the argon concentration by keeping the oxygen concentration in the intake air as constant (i.e. 21% by volume), this was achieved by adding one oxygen cylinder to the system. The nitrogen gas is replaced by the argon gas in the intake air.

SmartTrak 100 digital flow meter was used to measure Ar flow rate in terms of volume. XFM Stainless steel Multi-drop capability RS-232/RS-485, profibus DP digital thermal mass flow meter was used to measure the air rate of flow. WITT MM-2 K pressure fluctuation free gas mixture has been used to mix the argon and oxygen in required concentrations. Silicon chip fuel mixture display system has been used to control the air–fuel ratio, and it consists of Exhaust Gas Oxygen (EGO) sensor which is kept in the exhaust system and reads the exhaust gas continuously. Based on the results it monitors the air–fuel ratio by generations corresponding to output voltages. Engine Management system continuously reads this information and adjust the air–fuel mixture to provide maximum power and low emissions. Brief technical data are shown in Table 1.

Gasoline with 95 octane number, carburetor under full throttle opening and an ignition timing of 22° BTDC was used for the experiments. A Kistler model 6005 Quartz high pressure engine combustion sensor was used to measure the engine cylinders combustion pressure.

A PicoScope 4423 oscilloscope, 2000 A current clamp, 60 A current clamp 4 channel digital oscilloscope was used to measure and record various signals. Oscilloscope is fed with the amplified signals from the pressure sensor and degree marker. PicoScope is fast and accurate enough in the measurement, storing and analysis of high-speed phenomena. The input signal could be stored at the rate of up to 1500 MHz. Five sets of wave forms can be saved and fed to personal computer for computational analysis.

| Table 1 Engine specifications. |
|--------------------------------|
| **Engine specifications**      |
| Number of cylinders           | 1 |
| Bore                          | 95.12 mm |
| Stroke                        | 71.5 mm |
| Displacement volume           | 1297 cc |
| Maximum speed                 | 3500 rpm |
| Max. Cylinder pressure        | 130 bars |
| Compression ratio             | 8 Constant |
| Ignition timing, deg. BTDC    | 22 |
| Cooling system                | Water cooled |
| Valve arrangement             | Two vertical over head valves |
| Max power                     | 6.76 kW @ 3500 rpm |
| Max torque                    | 18.7 N m @ 2600 rpm |
Ecom EN2 Electro Chemical gas analyzers were used to analyze the exhaust gasses of the engine. Murphy TDX6 Temperature Scanner/Pyrometer Swichgage with 6 channels, and type “J” and “K” thermocouples were used to measure the temperatures at various positions of test setup.

Thermal barrier coating

Thermal barrier coating system consists of a bond layer (NiCr, NiCrAl) which is an oxidation-resistant to serve as a substrate material and for insulation. NiCrAl powder, CaZrO3, and MgZrO3 were selected to coat piston and valves. Engine cylinder head was machined before applying the thermal barrier coating to maintain the compression ratio of the engine as same before and after TBC. The material removed by machining is equal to the amount of TBC by volume. After machining, cylinder head was grid blasted, and then both the valves and the cylinder head of the engine were first coated with NiCrAl as a bond coat, and over CaZrO3 was coated, piston was coated with MgZrO3 using an atmospheric plasma spray gun. Spray coating restores the original dimensions of the engine.

Table 2 shows the properties of piston alloy and coating materials. Table 3 shows the specifications of the ceramic coatings.

Experimental procedure

This work aims at studying the consequences of TBC’s and mitigation of inlet air by the inclusion of Ar gas in the test SI engine. The total number of experiments was planned and divided into four categories.

Experiments on gasoline engine with Ar inclusion at constant engine speed.

Experiments on gasoline engine with Ar inclusion at variable engine speed.

Experiments on TBC gasoline engine with Ar inclusion at constant engine speed.

Experiments on TBC gasoline engine with Ar inclusion at variable engine speed.

During the initial stages conventional engine with predefined values of oxygen and Ar was considered for the experiments. Keeping the oxygen always at 21% the ratios of argon to be from 0% to 15% have been selected in the mixture. First set of experiments were conducted at a constant engine speed of 2100 rpm keeping other parameters constant. A 3% increase in Ar concentration was chosen as a step to vary Ar concentration from 0% to 15%. Various output parameters like TE, BMEP, volumetric efficiency; specific fuel consumption, heat release rates, brake power, exhaust gas temperature and emissions (like NOx, CO2 and CO) were measured and saved.

In the second set of tests, the argon addition procedure has been repeated in same 3% step on the conventional engine by varying speeds and keeping the other engine parameters constant. The engine speeds selected are 2100, 2400, 2700, 3000 and 3300 rpm.

In third set of tests, the argon addition procedure has been repeated in same 3% step and the engine with TBC runs at the constant engine speed at 2100 rpm keeping the remaining engine conditions constant.

In fourth set of tests, the argon addition procedure has been repeated in same 3% step and the engine with TBC runs at the varying engine, keeping the remaining engine conditions constant. The engine speeds selected are 2100, 2400, 2700, 3000 and 3300 rpm.

| Specification               | Maximum error value | Relative error |
|-----------------------------|---------------------|----------------|
| Engine speed                | 0.01 rev/s          | 0.28%          |
| Engine torque               | 0.08 N m            | 3.26%          |
| Brake power                 |                     | 2.42%          |
| Brake specific fuel consumption |                  | 1.1%           |
| Exhaust gas temperature     | 0.1 °C              |                |
| Exhaust gas concentration   | 0.01 ppm            |                |
| (NOx)                       |                     |                |
| Exhaust gas concentration   | 0.1 ppm             |                |
| (CO, CO2, O2)               |                     |                |
| Flow rate of air            | 1.02 × 10⁻⁴ m³/s   | 1%             |
| Flow rate of argon          |                     | 4.3%           |
| Fuel flow rate              | 1 cm³               |                |
| Timer (time measurement)    | 10 ms               | 0.7% Flow rate |

Table 2

| Material | Thermal conductivity (W/m °C) | Thermal expansion 10⁻⁶ (µ/K) | Density (kg/m³) | Specific heat (J/kg K) | Poisson’s ratio | Young’s modulus (GPa) |
|----------|-------------------------------|-----------------------------|-----------------|------------------------|----------------|-----------------------|
| NiCrAl   | 16.1                          | 12                          | 7870            | 764                    | 0.27           | 90                    |
| CaZrO3   | 14.6                          | 11.5                        | 4780            | 698                    | 0.21           | 87                    |
| MgZrO3   | 15.3                          | 8.01                        | 5600            | 650                    | 0.2            | 86                    |

Table 3

| Parameters       | Values                  |
|------------------|-------------------------|
| Particle velocity| 400-500 mm/s            |
| Oxide content    | 1-2%                    |
| Porosity         | 1-8%                    |
| Powder feed rate | 40 g/min                |
| Current          | 550 A                   |
| Voltage          | 86 V                    |
| Spray distance   | 100 mm                  |
| Torch nozzle diameter | 5.2 mm             |
Experimental error analysis

Table 4 shows the error analysis of the each device used.

Results and discussion

An experimental study was conducted on a single cylinder, port fuel injection, four stroke, water cooled SI engine with Ar inert gas in intake mixture. Experiments were conducted on both conventional engine (i.e. without TBC) and thermal barrier coated engine. In this study the effect of Ar inclusion (keeping $O_2$ concentration constant at 21\% by volume) to the input air on the various out parameters of the engine was studied. The engine parameters have been kept at the values mentioned above. Experiments were conducted on a standard engine by diluting intake air with argon, without TBC. Later same experiments were conducted on a TBC engine by diluting intake air with Argon. The results of both the cases were compared (see Fig. 1).

Ar concentration effect on the engine (running at a constant speed of 2100 rpm) output parameters

Volumetric efficiency

At full load conditions the variation in volumetric efficiency for the standard engine (SE) and the Thermal Barrier Coated Engine (TBCE) is shown in Fig. 2a. The increase in the volumetric efficiency has been observed in SE with increase in Ar gas concentration, this is due to the increase in mixture density and mass flow rate because of argon density and molecular weight \cite{4}. A 9.93\% of supercharging was observed with the increase in volumetric efficiency from 81.3\% (at 0\% Ar) to 91.23\% (at 15\% Ar), which effect the power output and specific fuel consumption.

Volumetric efficiency of an engine depends on ambient and working conditions of the engine. Increase in combustion chamber walls has been observed because of the reduced heat rejection with the addition of thermal insulation in TBCE.

At full load condition a volumetric efficiency drop from 3.3\% (at 0\% Ar) to 3.73\% (at 15\% Ar) and a maximum drop of 3.89\% (at 9\% Ar) full load condition of TBCE compared to uncoated condition (or SE). The variation in reduction of volumetric efficiency in both the cases was due to the higher cylinder temperature in low heat rejection (LHR) mode \cite{8}.

Brake specific fuel consumption (bsfc)

Fig. 2b gives the variation of the bsfc with increase in argon percentage for SE and TBCE. The figure shows the decrease in bsfc with the increase in Ar concentration. Reduction in bsfc of the engine was observed with increase in Ar concentration, the reason behind the reduction in bsfc is because of increase in BMEP by adding more Ar. A total drop of 17 g/kW h for SE and 18.2 g/kW h for TBCE is observed with an increase of argon concentration from 0\% to 15\%. Because of the increased surface temperature of the cylinder wall, the load bearing capability of the engine increases so the bsfc readings of TBCE are less than those of the SE. A maximum bsfc difference of 3 g/kW h is observed in the coated condition at full load compared to uncoated condition.
Exhaust gas temperature

The effect of Ar addition on exhaust gas temperature can be seen in Fig. 2c. Fig. 2c represents the decrease in exhaust gas temperature from 725 °C (at 0% Ar) to 661 °C (at 15% Ar) with a total drop of 34 °C. Fast diminishing of combustion temperature decreases the exhaust gas temperature during the expansion stroke. With increase in argon percentage the drop rate of combustion temperature during expansion stroke will be more.

Results indicate an increase in exhaust temperature in TBC engine compared to SE. A maximum increase of 21 °C may be seen between the two cases. The adiabatic condition created by ceramic coating (the quantity of heat blocked by coating is transferred to the exhaust gas) has lead to such increased exhaust gas temperature.

Effect of Ar inclusion on the engine exhausts emissions

NOx emission

Fig. 3a presents the lower NOx levels in standard engine (SE), and higher NOx levels in TBCE, point to remember that in both the cases argon gas was introduced into intake air mixture. Compared to normal engine without TBC and argon gas in inlet air mixture the NOx emissions were lower in both the SE and TBCE cases, but between the two SE emitting lower NOx compared to TBCE. With faster combustion process the combustion temperature increases and adiabatic effect of ceramic coating improved heat release rates because of these both reasons NOx levels in TBCE engine caused are high.

The reason behind the low NOx emissions in SE than TBCE is because of the inclusion of Ar in the intake air by reducing the concentration of nitrogen. A 55% reduction in NO emissions was observed in the engine emissions by the replacement of N2 (19% by mole fraction) by Ar and increase in air fuel ratio.

CO emission

Fig. 3b depicts the carbon monoxide levels in the exhaust gas from both SE and TBCE. Inclusion of Ar gas in the intake air resulted in an increase of CO from 85 (at 0% Ar) to 91.2 g/kgf (at 15% Ar) with Ar addition. This increase may be because of the unavailability of the oxygen during combustion with the
addition of argon. One more reason may be because of the faster drop in combustion temperature during exhaust stroke make the formation of CO₂ from CO. Increase in argon gas concentration reduces the exhaust gas temperature, at lower exhaust temperatures CO cannot react with O₂ to form CO₂.

In the case of TBCE the reason for less CO emissions may be because of the adiabatic conditions created by the ceramic coatings. The exhaust gas temperature will be higher in TBCE when compared with SE; this facilitates the formation of CO₂ from CO and O₂ reaction at suitable high temperatures. A maximum drop of 3.3 g/kg can be seen in case of TBCE.

**CO₂ emission**

The effect of Ar addition on CO₂ emissions can be seen in Fig. 3c. With the addition of argon the CO₂ emissions increase first during the argon concentration between 3% and 6% and then it decrease. The increase in CO₂ emissions in the early concentrations of argon may be because of the increase in air fuel ratio and availability of more oxygen, but as the argon concentration increases further exhaust oxygen reduces so the CO₂ emissions decrease.

The CO₂ emission is more in case of TBCE, while they are less in SE. The variation in CO₂ emissions is because the exhaust gas temperature is more in TBCE than in SE, this is due to the adiabatic effect of TBE; this facilitates endothermic chemical reaction between CO and O₂ to form CO₂. With increase in Ar concentration the exhaust gas temperature was decreased in both the cases of SE and TBCE so the CO₂ emission decreased.

**Engine speed**

The effect of increasing the engine speed from 2100 to 3300 rpm in 300 rpm step on the output parameters is presented in the following sub-sections. The effect of engine speed on the brake power (BP), volumetric efficiency, bsfc, and exhaust temperature are discussed below.

**Effect of engine speed on exhaust gas temperature**

The effect of engine speed on the exhaust gas temperature is shown in Figs. 4a and 4b. The increase in exhaust temperature was due to the fact that as the engine speed increases the mass flow rate of the engine increases this leads to the increase in heat release rate per cycle due to more fuel burnt per cycle.

In case of TBCE the exhaust gas temperature will be much higher due to the adiabatic effect of the ceramic coating.

A average increase of around 25 °C can be seen in exhaust gas temperature between SE and TBCE at 0% Ar and 2100 rpm. The same will be around 28 °C at 15% argon and 3300 rpm.

**Effect of engine speed on volumetric efficiency**

Increase in volumetric efficiency is shown in Figs. 4c and 4d with the increase in the engine speed from 2100 rpm to 3300 rpm. The volumetric efficiency increases with increase in engine speed, and this is due to fast cycle completion this eliminates the charge heating due to heated combustion chamber walls and back flow possibilities. The drop in volumetric efficiency in TBCE is due to increased combustion chamber surface temperatures leading to charge heating.

**Brake power**

The change in brake power variation with change in engine speed and argon concentration was shown in Figs. 4e and 4f. The Fig. 4e depicts the variation of brake power in a standard engine with varying argon gas concentration, where as Fig. 4f depicts the same in a thermal barrier coated engine.
Figs. 4e and 4f depicts a slight increase in brake power increases with increase in argon percentage and remarkable increase in brake power can be observed with increase in engine speed in both SE and TBCE. The increase in engine speed leads to the increases in volumetric efficiency and mass flow rate of intake air and in turn leads to the increase of engine torque and brake power. The power output will increase as the more fuel fed to the engine with increase in intake air.

There is a slight increase in brake power with TBCE when compared with SE. This may be because of the increase in energy due to the TBC. With the heat rejection to the walls of the cylinder decreases the available energy for the work output will increase, which increases the brake power. A total increase of 1.7 kW can be observed when argon percentage is zero and 1.93 kW increase when argon percentage is 15%. An increase in brake power of around 0.2 kW can be observed in TBCE compared with SE during 15% argon injection.

Brake specific fuel consumption
Figs. 4g and 4h depict the variation of the bsfc against the variation in engine speed and Ar concentration in SE and TBCE respectively. It is observed from figures that increasing the engine speed led to the increase in the bsfc.

This is because increase in engine speed increases the volumetric efficiency which leads to increase in mass flow rate of air as a consequence the mass flow rate of fuel should also increase. As the engine speed increases the engine power output increases but the increase in power output is overwhelmed with the increase in fuel flow rate so the bsfc decreases (as bsfc = fuel flow rate/power output).
The bsfc decreases with thermal barrier coating, and this may be of higher surface combustion chamber temperature. TBCE engines suffer with loss in volumetric efficiency; this reduces the air fuel ratio thereby decreases the bsfc. Simply TBCE is mainly intended to increase the energy of the engine, so we can expect the positive results in bsfc.

Conclusions

In this work, a performance and emission analysis was done to study the effect of thermal barrier coating on cranny and wall stifle regions temperature and argon gas in the inlet air mixture. Based on the results of this study it has been observed that, as the argon concentration increases the bsfc decreases. Decrease in volumetric efficiency has been observed with increase in argon percentage. As the Ar concentration increases the emission index of nitrogen oxide (NO), oxygen (O₂), nitrogen (N₂) and carbon dioxide (CO₂) was decreased. Increase in CO emissions has been observed with increase in argon addition to intake air. Exhaust gas temperature decreases with increase in argon concentration. Compared to SE lower bsfc has been observed in TBCE. This is because of adiabatic effect of ceramic coating. Volumetric efficiency drop was observed in TBCE because of increase in wall surface temperature of the combustion chamber. An increase in exhaust gas temperature was observed in TBCE because of the adiabatic effect of thermal barrier coating. Slight increase in NOₓ has been observed in TBCE than SE, this may be due to increased exhaust gas temperatures. Decrease in CO emission was recorded in TBCE than SE, this may be due to conversion of CO to CO₂ by reacting with O₂ at available high exhaust temperatures. CO₂ emissions got increased in TBCE; the reason may be because of conversion of CO to CO₂ at higher exhaust temperatures. With increase in engine speed the exhaust gas temperature increases in both SE and TBCE, but they are higher in TBCE than in SE, the reason may be due to adiabatic effect of ceramic coating. Rise in volumetric efficiency has been observed in both the cases of SE and TBCE run with increase in engine speed. As the engine speed increases a slight drop in volumetric efficiency has been observed in case of TBCE compared to SE. The improved energy in TBCE resulted in better brake power in TBCE when compared with SE. Decreased volumetric efficiency causes drop in bsfc in TBCE when compared with SE as the engine speed increases.

Conflict of Interest

The author has declared no conflict of interest.

Compliance with Ethics Requirements

This article does not contain any studies with human or animal subjects.

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