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Emissions analysis of an SI engine with humidified air induction

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Abstract

In this experimental research, the effects of humidified air induction on emissions of an SI engine have been investigated. Experiments have been performed on four-stroke SI engine fuelled with unleaded gasoline at two loads (50 % and 100 %) and four engine speeds (1200, 1400, 1600 and 1800 rpm) for 35 % and 80 % relative humidity. The experiments were first made with 35 % humid air, then the relative humidity of the intake air was increased 80 % with water injection and the same experiments were repeated. Exhaust emissions such as NO_x, CO, HC and CO₂ were measured and compared for each test condition. The results show that enhancement the relative humidity of the inducted air from 35 % to 80 % reduced the NO_x, CO₂, CO and HC emissions at full engine load with an improvement in brake thermal efficiency.

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1. Introduction

Since the invention of spark ignition engine, they have been used in automobiles, motor roads, motorbikes and to power many other devices. In general, spark ignition engines operate on burning petroleum-based fuels to cylinders and produce exhaust emissions that are the major contributors to air pollution [1]. Main pollutants from the spark ignition engine exhaust are carbon monoxide (CO), carbon dioxide (CO₂), hydrocarbons (HC) and nitrogen oxides

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(NO_x) [2]. Since these emissions have a major impact on the human health and environment [3, 4], strictest emissions regulations have been imposed to reduce exhaust emissions [5, 6].

Reduction of exhaust emissions and improve the fuel economy is the main challenges facing the automotive industry. Though harmful exhaust emissions are reduced effectively by using costly and complex after-treatment devices, enacting new strict emissions norms necessitate a lot of effort for further reduction in pollutant emissions and improving the fuel economy [7].

One of the most hazardous emissions of spark ignition engine is NO_x emissions since it reacts in the atmosphere to form ozone which is a major constituted of photochemical smog [8]. Also, NO_x emissions lead to formation acid rain. NO_x is produced in combustion chamber mostly from nitrogen in the atmospheric air [2]. NO_x is a mixture of nitrogen-oxygen combination and it mainly consists of nitrogen oxide (NO) [8].

Modern spark ignition automobiles are equipped with three-way catalytic converters that reduce CO, HC and NO_x emissions simultaneously. To get high converter efficiency, it is necessary to operate the engine at the stoichiometric air-fuel ratio. The problem is that three-way catalytic converters are very inefficient for NO_x reduction when the engine runs with lean air-fuel mixture [8]. However, it is possible to minimize NO_x emissions by other techniques such as exhaust gas recirculation (EGR) and water introduction technologies such as direct water injection into the cylinder using high-pressure injector, spraying water into the intake manifold, water-fuel emulsions [9] and steam injection [10]. NO_x can be reduced by using EGR, which reduces the oxygen concentration in the combustion chamber that lower the cylinder temperature but it would increase HC and CO emissions [11]. The benefits of water introducing into the combustion chamber are reducing the peak flames temperature and hence reducing the formation of NO_x emissions [9–13]. This phenomenon mainly occurs by the three effects of introduction water into the cylinder which can be explained as:

- A chemical effect as a result dissociation of water at high temperature in active radicals [14];
- A thermal effect as due to the higher heat of evaporation for water than that of gasoline that leads an improvement in volumetric efficiency;
- A dilution effect as a result replacing by air with water vapor in the inlet manifold of the engine.

All above-mentioned effects led to a significant reduction in-cylinder temperature and so on NO_x emissions are decreased [14]. In addition, these effects not only reduce NO_x emissions but also can increase the thermal efficiency [15, 16].

Minimizing the NO_x emissions via different water addition techniques has received great attention recently and has been suited by many researchers [10–14]. However, the effects of humidified air on SI's emissions are still lacking in existing literature. Therefore, the main objective of this study is to experimentally investigate the effects of humidified air on the main emissions of SI engine. Apart from other water introduction techniques, in this study, the relative humidity of the inducted air is increased by adiabatic humidification process as an original concept in engines.

Actually, adiabatic humidification is commonly used in the air conditioning applications especially in hot climate areas and in various industries. In the adiabatic humidification process, water is atomized into the air with help of nozzles and water droplets present into the air get evaporated and achieve a gaseous state. The required energy for the evaporation is drawn from the surrounding air in the form of heat. This leads to a drop in the air temperature up to 10 °C that this is known as an adiabatic cooling effect [17]. Also, the evaporated water enhances the air's moisture content and hence the humidity of air increases.

2. Description of the experimental setup and test procedure

The experimental setup mainly consists of a single cylinder spark ignition engine, dynamometer, exhaust gas analyzer, humidification unit, flow meters, thermocouples and control unit. A detailed schematic view of the experimental setup is shown in Fig. 1. The test engine used in this research was a four-stroke and water-cooled spark ignition engine with a bore of 87.5 mm and a stroke of 110 mm. The rated power of the engine is 4.5 kW at 1800 rpm. The engine was coupled with an eddy-current dynamometer. The unleaded gasoline used in this work was obtained from a local petrol station. The experiments were carried out at the half and full loads for the engine speeds of 1200, 1400, 1600 and 1800 rpm with induction of 35 % and 80 % relative humidified air. For that,

a humidification unit was installed. The humidification unit includes a water pump with maximum mass flow rate 2 liters/minute, water filter, water nozzle, an insulated big air box with a volume of 320 L, relative humidity sensor, temperature sensor and control unit. The high-pressure water nozzle was mounted on the airbox head. The relative humidity of the air was arranged by adjusting the water injection quantity. For this purpose, an electronic control unit was used to obtain desired relative humidity of the inlet air. The engine experiments were conducted under constant spark timing (10 CA bTDC) and compression ratio (8:1). For a specified engine speed and load, the throttle valve position was fixed to obtain the same brake power for each relative humidity ratio of air uses. During the experiments, all data were taken after steady-state conditions were reached and all measurements were repeated at least four times at each test point and the average values were used to minimize the systematic error. Exhaust emissions such as carbon monoxide (CO), hydrocarbon (HC), carbon dioxide (CO₂) and nitrogen oxides (NO_x) were measured using an exhaust gas analyzer. Technical specifications such as measurement ranges and accuracy of the exhaust gas analyzer are given in Table 1.

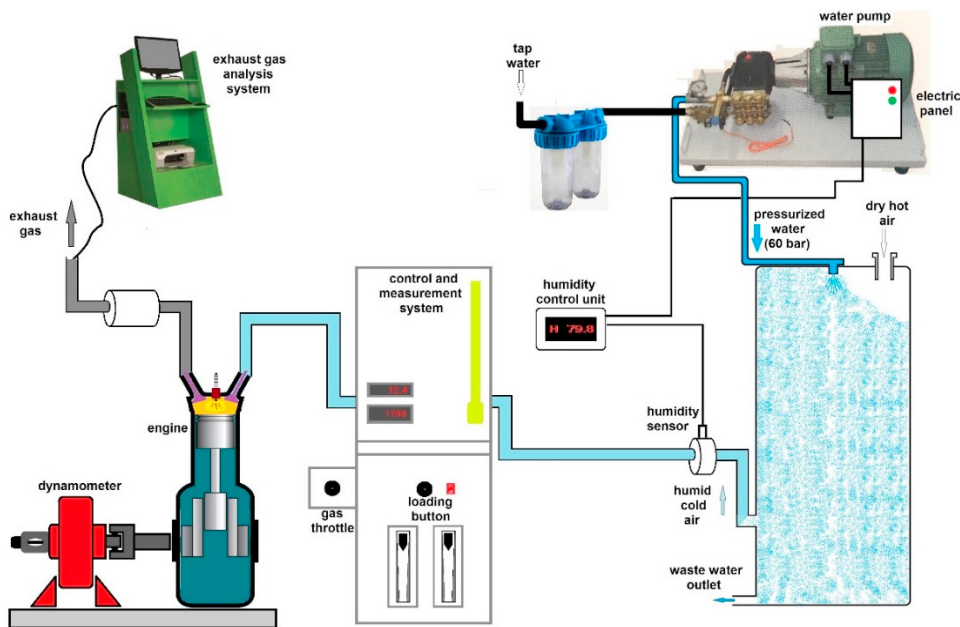


Fig. 1. Schematic view of the experimental system.

Table 1. Technical specifications of exhaust gas analyzer.

Emissions	Measuring Range	Accuracy
CO	0–10 % vol.	0.001 %
CO ₂	0–20 % vol.	0.01 %
HC	0–4000 ppm	1 ppm
O ₂	0–25 % vol.	0.01 %
NO _x	0–4000 ppm	1 ppm

3. Results and discussion

In this section, the effects of humidify inlet air on NO_x, CO₂, HC and CO emissions of the test engine are graphically presented and detailed discussed. In the graphic labels, H denotes the relative humidity of the inlet air and L implies the engine load. For example, H35_L50 means that the relative humidity of the inducted air is 35 % and tests are performed at 50 % engine load.

Fig. 2 shows the effect of humidified air on NO_x emissions for the engine loads of 50 % and 100 %. As seen in Fig. 2 at all engine speeds, the maximum NO_x emissions and the minimum NO_x emissions were measured for 35 % and 80 % relative humidity at 100 % and 50 % engine load, respectively. A significant decrease in NO_x emissions occurs when relative humidity ratio of the inlet air is enhanced from 35 % to 80 % for two engine loads. The increasing the relative humidity from 35 % to 80 % reduced NO_x emissions at averagely 52.75 % and 34.77 % for half and full engine load, respectively. Formation of NO_x in the cylinder is affected by many factors, however, it strongly depends on upon in-cylinder temperature, oxygen concentration and combustion duration [2]. With increasing the humidity of inlet air, its moisture content also increases. As well-known that the heat of vaporization of water is higher by about a factor of 7.6 than that of gasoline. Therefore, the evaporation of introducing water droplet into inlet air reduces the intake charge temperature (approximately 5 °C in this study) that causes to fall the temperature at each point of the cycle. Moreover, due to the high heat capacity of the water, the peak in-cylinder temperature was reduced and consequently, NO_x emissions are decreased [18]. Other reasons for the reduction of NO_x emission could be dilution effects due to water vapor that reduces the oxygen concentration in the combustion chamber [19]. NO_x emissions at half load are comparable to those at full load. For the equal relative humidity, more NO_x emissions are emitted at full load than that of half load due to rich fuel-air mixture operation.

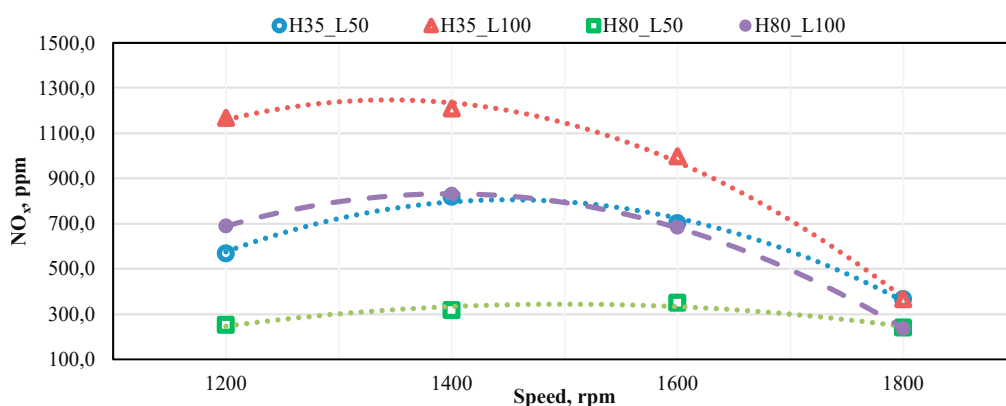


Fig. 2. Effects of humidified air induction on NO_x emissions under half and full engine load.

The effect of humidified air induction on CO_2 emissions of the test engine is shown in Fig. 3. As seen in this figure a significant decrement in CO_2 emissions was achieved with 80 % relative humidity at full engine load. This is a promising result since CO_2 emission is a greenhouse gas that is the reason why many countries committed to reduce the CO_2 emission levels [20, 21]. In case of 80 % relative humidity, CO_2 emissions were decreased by about 15.83 % and 12.90 % at the half and full engine loads, respectively.

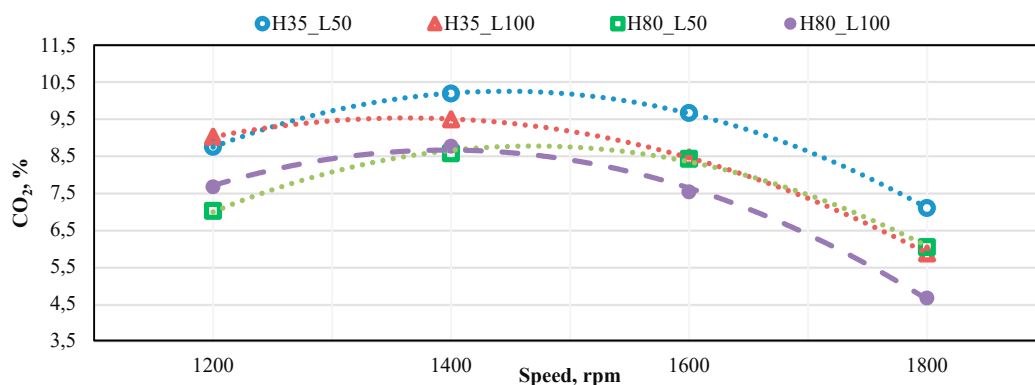


Fig. 3. Effects of humidified air induction on CO_2 emissions under half and full engine load.

The effects of humidified air induction on HC emissions under half and full engine loads are illustrated in Fig. 4. It is clearly seen in this figure that increasing the relative humidity of the inlet air results a significant decrement in HC emissions at full engine load whereas entire the engine speed range the maximum HC emissions are produced with a relative humidity of 80 % at half engine load. From here it can be concluded that HC emissions are more affected by the engine loads compared to a relative humidity of the inlet air. At full engine load due to high charge mass flow rate into the cylinder the burning of the fuel is improved and this gives lower HC emissions when compared with half engine load for the same relative humidity. It is calculated that HC emissions were reduced by about 22.21 % with full engine load for the 80 % relative humidity as compared to half engine load.

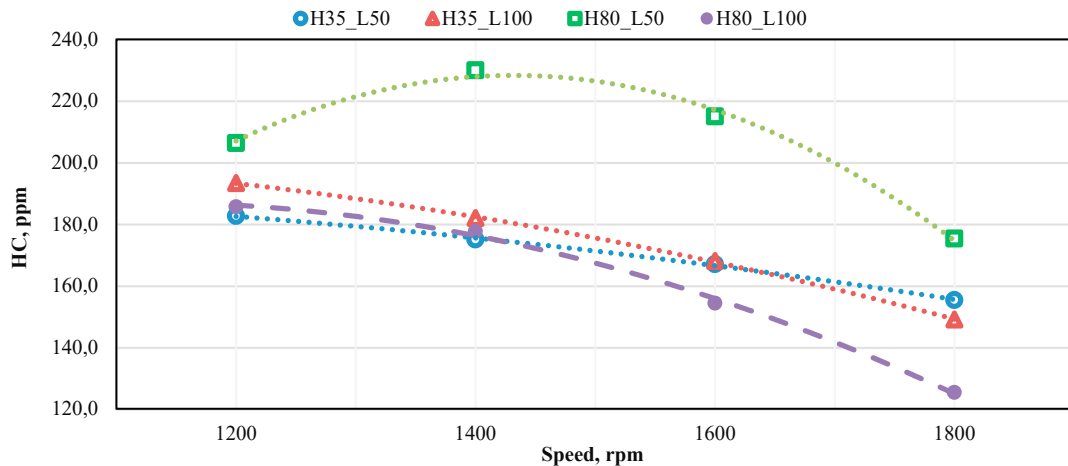


Fig. 4. Effects of humidified air induction on HC emissions under half and full engine load.

Fig. 5 shows the effects of humidification of inlet air on CO emission. As seen in this figure maximum and minimum CO emissions were measured for the 80 % relative humidity at the half and full engine loads. This tendency also observed in HC emissions. Therefore, the possible reasons for the lowest CO emissions with 80 % relative humidity at full engine load would be mentioned above explanation. Also, due to lower combustion temperature with 80 % relative humidity, dissociation rate of CO_2 into CO and O_2 are reduced that ensures less CO emissions. Moreover, the lowest CO emissions for 80 % relative humidity could be associated with the water-gas shift reaction that influences the emissions by converting CO to CO_2 and generating H_2 from the water steam.

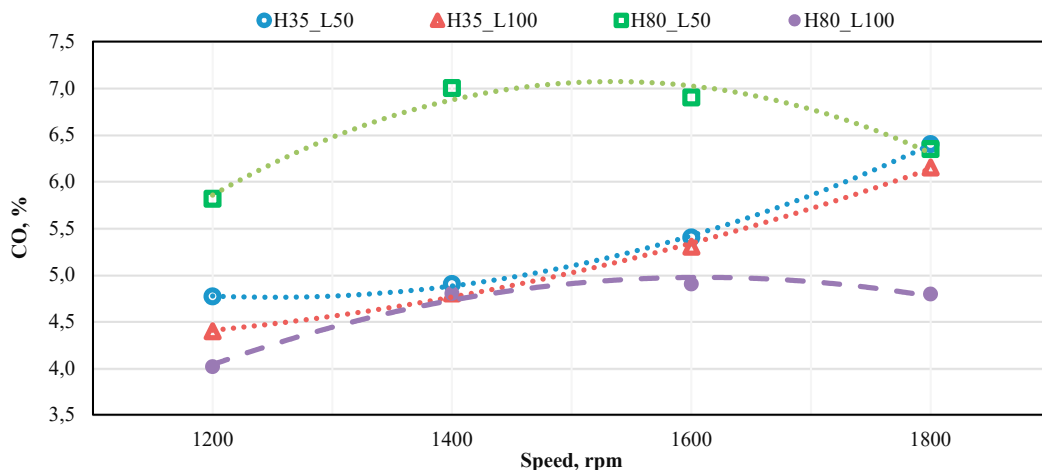


Fig. 5. Effects of humidified air induction on CO emissions under half and full engine load.

The effects of humidification of inlet air on the brake thermal efficiency were also determined and illustrated with Fig. 6. As seen in this figure brake thermal efficiency of the engine is increased by increasing both engine load and relative humidity of the inlet air. It was determined that average increase in thermal efficiency by 80 % relative humidity is 2.77 % when compared with 35 % relative humidity at full engine load. Since high relative humidity reduces the in-cylinder temperature, heat transfer from the cylinder wall also may reduce that increases the brake thermal efficiency [22].

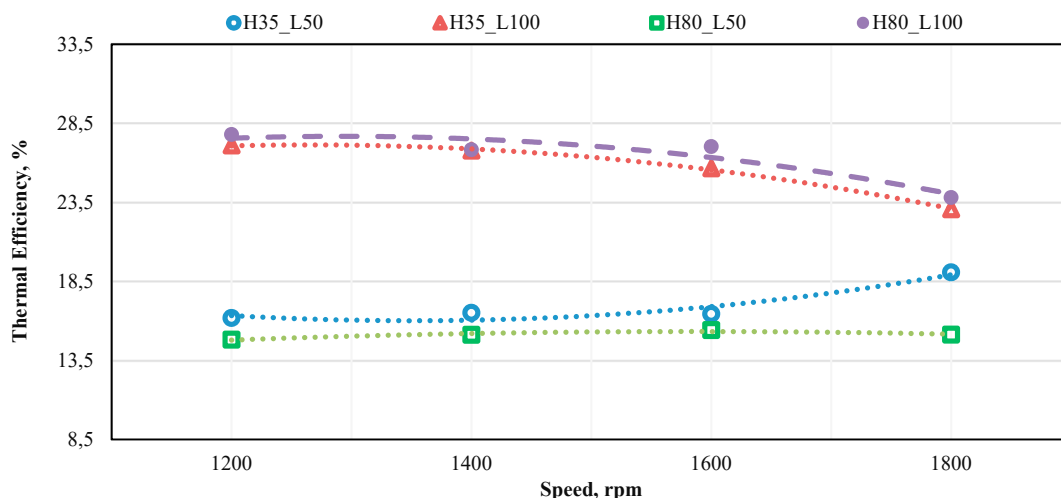


Fig. 6. Effects of humidified air induction on brake thermal efficiency under half and full engine load.

4. Conclusions

The aim of this experimental research is to investigate the adiabatic humidification of inlet air on main emissions of an SI engine. The result indicates that increasing the relative humidity of the inlet air from 35 % to 80 % show great benefits in terms of both exhaust emissions and thermal efficiency. The highest reduction in CO, HC and CO₂ emissions and the highest brake thermal efficiency was achieved with 80 % relative humidity at full engine load. The minimum NO_x emissions occur at half engine load with 80 % relative humidified induction air. In general, it is concluded that adiabatic humidification of engine's inlet air is a promising way to reduce exhaust emissions without any deteriorating in engine performance. The authors are also planning to further investigate the effects of adiabatic humidification with oxygen enrichment on exhaust emissions and performance of an SI engine.

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