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Review Article

EGR EXHAUST GAS OPTIMIZATION, POLLUTANT-REDUCTION APPROACH

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ABSTRACT
One of highly important achievements of automobile world in the twentieth century was catalytic converters designing and making which reached its peak in the late 2oth century, providing three-way converters. In fact, catalytic converters which are small chemical processors introduced to markets in the mid-1970s play vital and important role in this field concerning removal of three main pollutant groups resulted from inter combustion engines. These three groups include Unburned Hydro Carbon, UHC, other carbon compositions which is carbon oxide (CO), and different types of Nitrogen Oxide (NOX). In addition to catalytic converters, Exhaust Gas Recirculation method, EGR, is one of the most effective and efficient methods to reduce Nitrogen Oxide pollutants emitted from spark ignition engines (inter combustion). Related tests were conducted on one gasoline engine named Motor 1725 in Iran Khodro Company. Experimental results showed that maximum temperature of EGR fluid is 430 Kelvin degrees in lab condition for the mentioned motor. These methods are efficiently used to optimize the air and to prevent air pollution in Iran.

Keywords: *Pollution Reduction, EGR, Combustion, Gasoline and Diesel Engines*

INTRODUCTION
The air quality is an extremely complex issue and it has long been the center of interest for scientists in universities, industries, and governmental associations worldwide. Their research goal was to reach better perception of the subject that how atmosphere pollution affects our environment and how it can efficiently be dealt with. Prior to explanation of how continuous display of air quality has been paid attention in this general image, some historical background of ideal environment will be taken in to account.

From Greece civilization onward, physicians and scholars have been confused toward Earth atmosphere secrets. According to the first major scientific progress in chemistry, Earth atmosphere includes Nitrogen (79 volume percentage), oxygen (20 volume percent), and a little water and CO_2 (Machacan *et al.*, 2010). During the 19^{th} and 20^{th} centuries, some eminent chemists and physicists enhanced our knowledge in this field.

Ramsey revealed the presence of Helium, Neon, Argon, Krypton, and Xenonin atmosphere. Other researchers found some evidence for presence of small amounts of methane, hydrogen, ozone, carbon monoxide, sulfur dioxide in the air as well as ions including Sulfate, Nitrate,, Ammonium, and dissolved chloride in water rain (Hawley *et al.*, 2012).

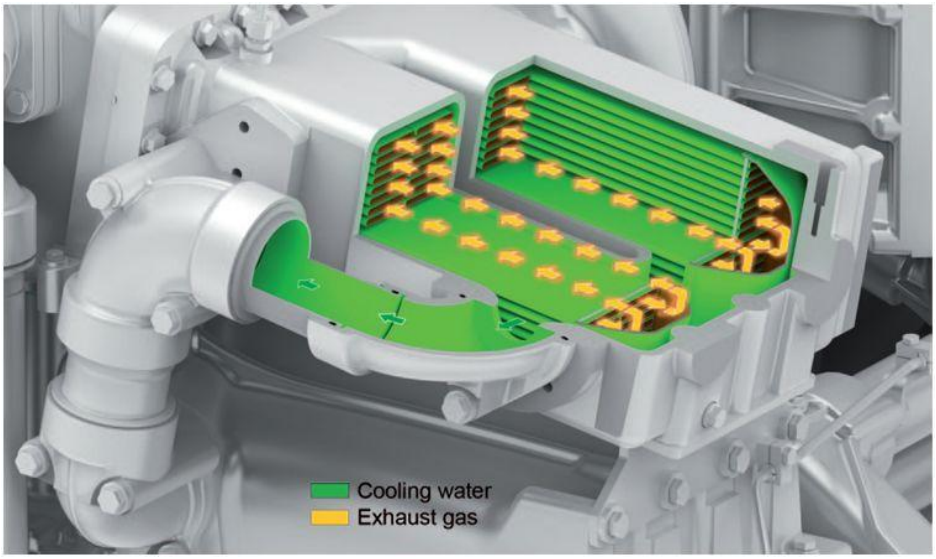
Therefore, at the beginning of 1950, limited amount of information was collected toward chemical mixture of atmosphere. Since 1950, rapid advances in analytical chemistry and advent of high-speed computer technologies have resulted in an explosion of information about atmospheric composition and it was clear that atmosphere is the real source of many gases and Ayrumuls with concentration of less than PPM (VOL) which can affect environment despite small amount of methane (Heil *et al.*, 2014).

Problem Description
Air Pollution

Air pollution is, based on the engineering joint in air pollution and its control in the Unites States: Existence of one or more pollutants in outdoor space of homes such as dust, soot, gas, suspended liquid, odors, smoke, fume, and mist or vapor in the size or durationthan can be hazardous and harmful for

human life, plants, or animals as well as intervention in pleasure and comfort of community without reasons.

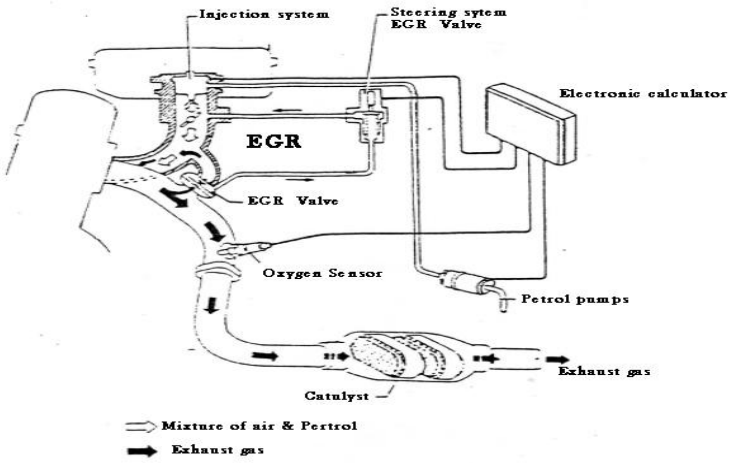
Air is the most essential material for survival of living creatures. Each creature consumes 16-22 kilograms of air on a daily basis (Bowen, 2013); however, he only uses only 1.5 kilograms water and nearly one kilogram of food.



According to importance of air in accordance with air pollution in human life, it is almost 11 and 16 times as dangerous as water and food pollution, respectively. Nevertheless, millions of tons of pollutants enter Earth atmosphere annually. Human need to air is more than water and food. This is mainly because human beings can survive without food for up to 5 weeks and can live for five days without water but cannot live up to five minutes without air. One important features of essential air is its cleanliness. Air cleanliness and freshness have been the center of attention from the past. Like for instance, Hippocrates has considered clean air as the most important and the most effective principle of public health. Iranian famous scientist, Avicenna, considers the presence of dust in the air as one of the short life span factors (Patel, 2012).

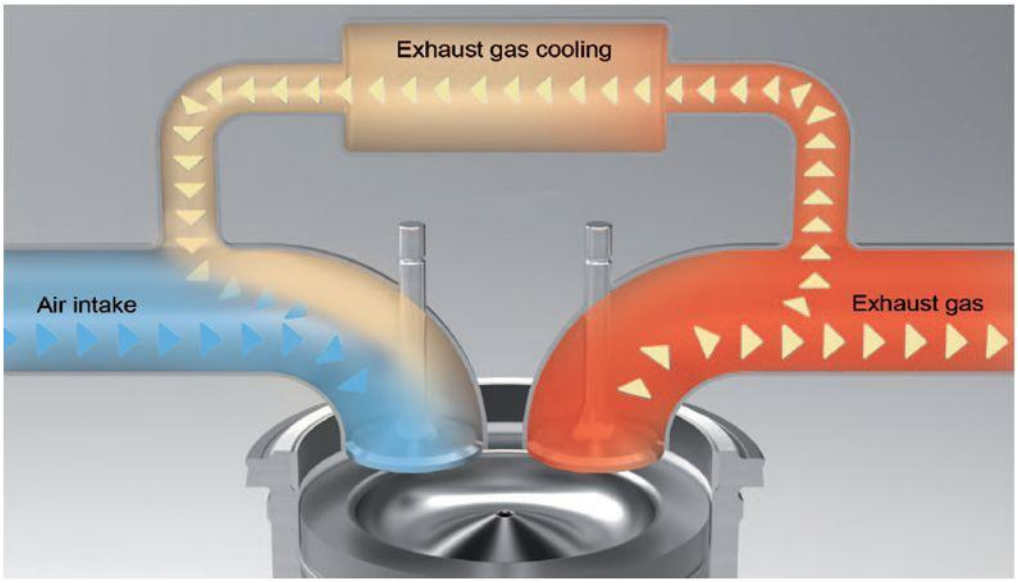
Definition, History, and Discussion of EGR

Exhaust Gas Recirculation, EGR, is one of common methods to produce thin mixture.



EGR system and catalyst in one motor

In this method, some amounts of exhaust gas are directed to downstream carburetor throttle by one adjustable valve through one connecting pipe. Flame speed and peak combustion temperature reduce due to thin air-fuel mixture as a result of mixing with EGR, leading to reduce NO amount. EGR, among various methods to reduce NO pollutant in combustion chamber, is the simplest, the most economic, and the most effective method and it can display fuel economy and better drivability. It is better in comparison with other methods such as delayed ignition, or poor or rich mixture (Farrauto and Voss, 2013).



Increased amount of EGR leads to reduced maximum temperature of cycle. The results of this experience show that in addition to reduced NO; UHC and CO pollutants increase in exhaust gas through EGR.
The main and major effect of EGR gas in unburned gas (new mixture) in NO pollutant formation procedure is reduced flame and burned gas temperature as a result of heat capacity inside the cylinder per fuel mass unit.
Similar information obtained separately concerning the effects of burned gases on temperature of gases inside combustion chamber by changing valve overlap angles, compression ratio, and EGR shows that, under real working condition of motor, total thermal capacity of mixed diluters inside cylinder are important and how the level of these diluters changes including valve overlap angles, EGR amount, and compression ratio is not important.
EGR and poor combustion (a mixture with air more than stoichiometric level) are two common methods used to control NO pollutants and to reduce fuel consumption and each of them enjoys some advantages and disadvantages.
EGR method, in addition to considerable reduction of NO, can be used as a tool to reduce fuel consumption in motors with advanced combustion chamber. The negative effect of EGR is more on combustion rate rather than air. Thus, increasing less amount of EGR leads to rapid increase of combustion duration and reduced combustion efficiency and even, inserting 7% or EGR leads to half-reduced NO pollutant; however, poor combustion is a better method rather than EGR as a method to correct fuel economy (Bowen, 2013). Modern gasoline motors work with stoichiometric air-fuel mixture. When EGR is not used, the mass of entered fuel-air mixture to cylinder controls torque and engine- power output. If we intend not to change torque and engine- power output while adding EGR, then trapped mixture mass should not be changed inside the cylinder. That is why, according to Figure (6-3), entered EGR to cylinder needs to be added to trapped fuel and air. Thus, total mass inside the cylinder (air-fuel and EGR) will be 0.4 grams to obtain fixed torque and power and since cylinder volume is fixed, increased trapped mass will only be possible by rising mixture density.

The Effect of EGR on Cylinder Load

Considering the fact that EGR entrance is connected to downstream of throttle in gasoline motors, to this end, EGR amount will not practically change the fuel-air mixture ratio and the effect will only be on entering mixture to the cylinder (Tomazic and Pfeifer, 2012)

The Effect of EGR Dilution

The highest amount of EGR includes H_2O, CO_2, and N_2 which does not have any positive effect on combustion. EGR in each equivalence ratio is accompanied by reduced oxygen of mixture called mixture dilution (Weiss, 2013).

EGR Heat Effect

A considerable number of researchers believe that since EGR specific heat is greater than that of the air, it can affect combustion and production of pollutants. On the other hand, trapped mixture temperature will rise at the beginning of compression due to high EGR temperature in comparison with air-fuel temperature (Heil *et al.,* 2014).

The Effect of EGR Thermal Losses

EGR gas can affect on thermal losses. This issue has been shown in Figure (7-3). As it can be seen, using EGR decreases motor thermal losses because peak temperature of combustion chamber reduces by EGR (Bowen, 2013).

In gasoline motors, most of whirlwind motion of cylinder is used to achieve rapid combustion. One of common methods in this type of motion is installing two air valves for each cylinder. In this condition, volumetric efficiency of the engine has been modified in high rotations and bemp value will be almost fixed, obtained in moderate to high rotations. During suctionphase, cylindrical vortex motion is created and initially intensified during compression phase in which the volume falls in compression phase and finally is converted to turbulent motion at final stages of compression phase. This type of motion is able to burn poor mixtures, to present better fuel economy, and to produce less pollutants. Advantages of cylindrical vortex motion are as following:

- Combustion-related reduced delay time from 0% to 10% of fuel weight.
- Combustion-related reduced combustion duration from 10% to 90% of fuel weight.
- Reduced changes of cycle to cycle, and in particular in poor mixtures.
- Tolerating more than 20% of EGR with fixed imep amount.
- Production of less NO_X pollutants.

In rapid combustion method, lessadvanceis needed to obtain MBT. To this end, ignition timing must be regulated. The temperature inside the cylinder rises by reduced ignition advance and consequently, flame speed increases. This action leads to reduced combustion delay, increased NO_X, and also increased motor sound in complete load (Hawley, 2012).

EGR Method can be used to meet such Disadvantages for more Diluted Mixture

1. One of other methods, advised by some researchers in order to reduce NO_X pollutant in gasoline motors, is to change ignition timing. When ignition occursearlier, the pressure of gases rises inside the cylinder because the highest amount of fuel is burned before Top Dead Center, TDC, and pressure peak occurs around Top Dead Center where cylinder volume enjoys the lowest amount. While delayed ignition happens, the pressure of gases falls inside the cylinder because the highest amount of fuel is burned after Top Dead Center where the piston is moving downward and cylinder volume is increasing. The higher the pressure of gases inside cylinder is, the more the temperature of burned gases will equally rise, and consequently level of NO_X pollutant will also rise. Delayed ignition leads to reduced level of NO_X (Due to temperature reduction). Figure 15-3 shows the changes of NO_X pollutant as a function of ignition timing for a gasoline motor and Figure 16-3 reveals the effect of delayed ignition on NO_X pollutant in gasoline motor working with 30% Isobutanol and gasoline. As it can be seen in figures, ignition timing affects strongly on NO_X pollutant and this effect is far more in poor mixtures than rich ones. Another point which can be added is that changing ignition timing reduces torque and motor power (Ishiki, 2013).

2. Another method to reduce the level of NO is adding water vapor or liquid water with low pressure to air-fuel mixture. When water is added to the mixture, it will absorb high amount of combustion-temperature heat to convert in to vapor due to the fact that water has greater evaporation latent heat.
So, it wills intake a small amount of combustion-chamber heat while warming up from initial vapor temperature to flame temperature. When it reaches flame temperature, it might be disintegrated and intake another amount of combustion-chamber heat. Consequently, these changes will lead to reduced temperature of combustion-chamber gases. This method has not yet commercially been used in order to reduce NO_X pollutant in motors (Farrauto and Voss, 2013).

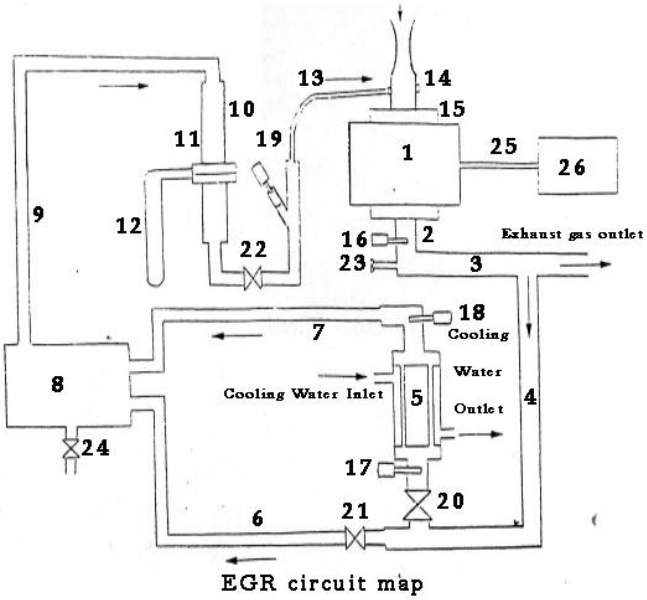
Analysis of Hypotheses and Research Test

EGR Fluid Flow in EGR Circuit

Combustion gases which have left exhaust manifold enter main exhaust pipe which has one thermocouple (16) and one sample- taking tube (23). To remove the effect of motor vibration on exhaust pipe, part of this pipe is made (3) up of steel proboscis pipe. From now onward, EGR fluid can be directed to motor in the form of cooled or non-cooled. If needle valve (21) is closed, EGR fluid will enter exhaust colorimeter (5). This colorimeter is cooled by city water and two thermocouple are used to control EGR temperature while entering and exiting to and from colorimeter (17 and 18). EGR fluid enters surgetank (8) after being cooled through steel pipe (7). If needle valve (20) is closed, EGR fluid enters surgetank (8) after without being cooled through steel pipe (6). Surge tanks are considered for two reasons:

- To merge pulse flow of EGR fluid
- To unify EGR fluid mixture

Then EGR fluid enters pipe (10) and weight (11) through steel pipe (9). To determine EGR flow rate, orifice flangesare equipped with water manometer (12). One needle valve (22) is used to control EGR fluid level. After re-controlling the EGR temperature by thermocouple (19), this fluid enters air manifold through carburetor Flange (14) (placed in downstream) and then enters cylinders after air-fuel mixture (to reduce thermal losses, EGR circuit has been isolated by glass wool).



EGR circuit map

Solutions for Pollution Reduction with Recommended Concept of Contamination

EGR is a method where exhaust gas, partially mixed with fresh air, returns in to cylinder. Exhaust gas is mainly made up of N_2 and CO_2. Since exhaust gas is not burned more, it can be recycled inside cylinder. When part of exhaust gas returns to cylinder, it acts as combusting diluter. Moreover, it reduces oxygen concentration inside combustion chamber. Specific heat of exhaust gas is far more than fresh air. Thus,

EGR increases specific heat of intake charge. Consequently, it reduces increased temperature for heat emission in combustion chamber.

Some of researchers have focused on methods to reduce NO_X from diesel motors. According to the method of Ming *et al.*, EGR can be used for diesel motors with higher efficiency than other techniques which reduce NO_X from diesel motors. He has reviewed paths and limitations to reduce NO_X outputs from diesel motors and he has highlighted the inevitable application of EGR. The effect of EGR on diesel performance was analyzed and various methods were introduced for EGR implementation.

Despite diesel motors, motors which have been charged homogeneously, like spark ignited gasoline motors or other motors working with gas fuel can effectively use λ control to reduce NO_X. To have one homogeneous charge, weakened mixture in mixture power can effectively reduce flame temperature and propagationspeed. A highly diluted mixture of fuel λ> 1.2-1.4 (Depending on type of fuel) can produce highly low-NO_X outputs. This trend of NO_X reduction with higher weakened charge continues until stable flame propagation is unsure. When highly diluted mixture is used, like for instance λ=1.8, the concept ofhomogenous charge compression can be used where motor action of fuel economy is improved through sudden fuel, normally producing low amounts of NO_X and PM (Machacon, 2010).

Exhaust Gas Recirculation

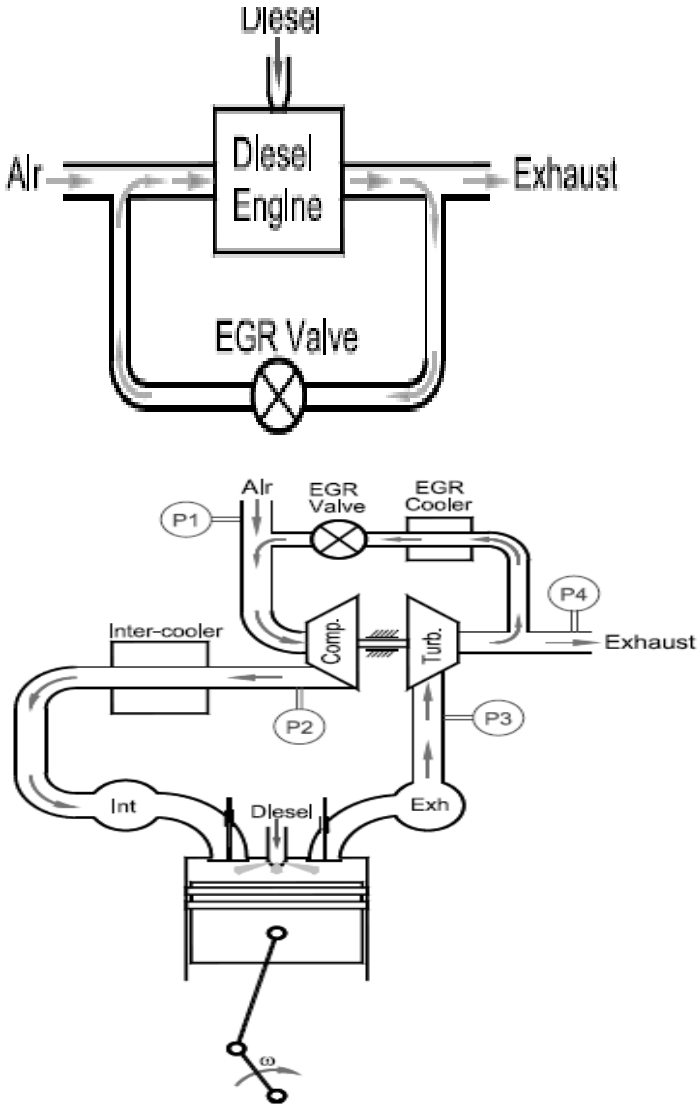


Figure 2: Low pressure loop EGR

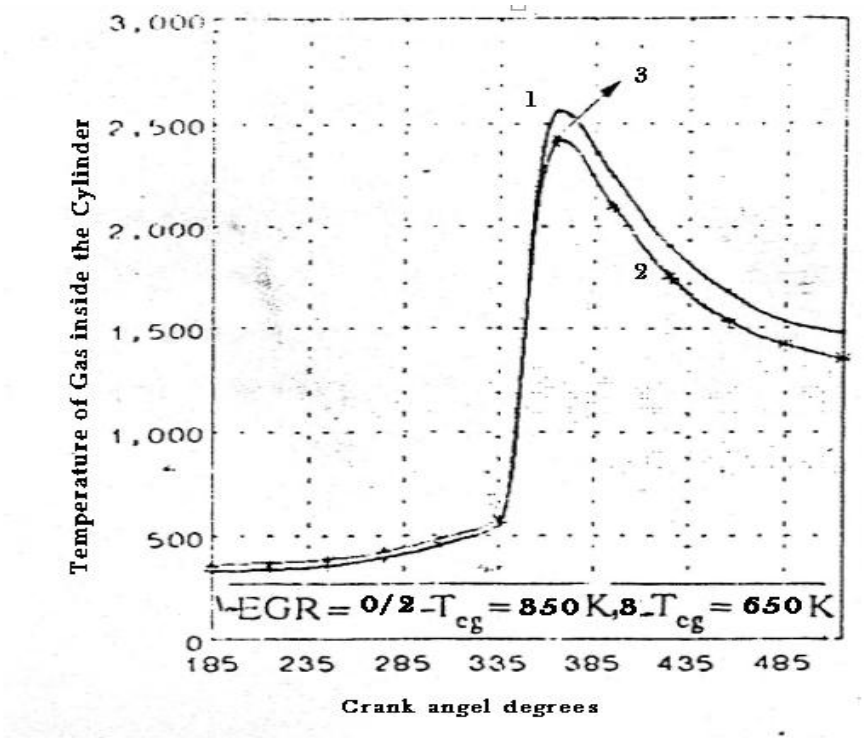
Among existing options, the most appropriate method to recirculate exhaust gas is exhaust gas recirculation from upstream turbine to downstream compressor, EGR pressure loops, in Figure 3.
Thus, compressor and intercooler are not exposed to exhaust. Such high-pressure loops are only applicable when upstream pressure of turbine is sufficiently greater than boost pressure (Murayama, 2015).
The temperature of diesel exhaust is usually between 120 to 720 degrees of centigrade for systems without turbocharged and 100 to 600 degrees of centigrade for turbocharge systems.
One of methods advised by researchers to reduce NO_X pollutant in gasoline motors is ignition -timing change. When ignition happens earlier, the pressure of gases rises inside the cylinder because the highest amount of fuel is burned before Top Dead Center and pressure peak occurs around Top Dead Center where cylinder volume enjoys the lowest amount. While ignition happens with delay, the pressure of gases falls inside the cylinder because the highest amount of fuel is burned after Top Dead Center where the piston is moving downward and cylinder volume is increasing. The higher the pressure of gases inside cylinder is, the more the temperature of burned gases will equally rise, and consequently level of NO_X pollutant will also rise. Delayed ignition leads to reduced level of NO_X (Due to temperature reduction) (Zheng *et al.*, 2013). Figure.…. shows the changes of NO_X pollutant as a function of ignition timing for a gasoline motor as well as the effect of ignition timing on NO_X pollutant in gasoline motor working with 30% Isobutanol and gasoline. As it can be seen in both figures, ignition timing affects strongly on NO_X pollutant and this effect is far more in poor mixtures than rich ones. Another point which can be added is that changing ignition timing reduces torque and motor power (Zheng, 2013)
Another method to reduce the level of NO is adding water vapor or liquid water with low pressure to air-fuel mixture. When water is added to the mixture, it will absorb high amount of combustion-temperature heat to convert in to vapor due to the fact that water has greater evaporation latent heat.
So, it will intake a small amount of combustion-chamber heat while warming up from initial vapor temperature to flame temperature. The result of these changes will be reduced temperature of combustion chamber. This method has not yet commercially been used in order to reduce NO_X pollutant in motors (Bown, 2013).
According to what was mentioned above, EGR method is probably the simplest and the most economic one, among various and effective methods recommended by researchers in order to reduce NO pollutant, and it seems that cooling this gas (cool EGR) can reduce NO negative effects on motor performance along with higher reduction of NO.

The Effect of EGR Temperature Changes on Temperature of Gases inside Combustion Chamber

When gasoline motor works in complete load condition (completely open valve), maximum produced power is obtained by rich mixture (λ=1.1 to 1.25). In this situation, because oxygen of mixture is less, the amount of nitrogen oxide pollutant produced by motor will be less and more EGR will not be necessary. In extremely low load, near Idle –nearly closed valve, because the amount of residual gas from previous cycle is more inside cylinder, EGR must not be used to control NO pollutant in this phase because entering EGR leads to motor stability removal. In low-load state, because poor mixture or in stoichiometric conditions (λ=0.9 to 1), the amount of emitted nitrogen oxide will be maximum due to presence of more oxygen in the mixture as well as sufficient temperature. So, EGR needs to be used to control NO pollutant in this phase. EGR gas is considered as residual trapped inside the cylinder from the previous cycle. The amount of EGR depends on pressure difference between exhaust pipe and manifold. The higher the amount of EGR is, the more the amount of gas will equally be, and consequently the load inside cylinder and finally released energy reduce. General effect of residual gas is increased specific temperature of gases obtained from combustion, leading to reduced maximum combustion temperature.
Fuel-air ratio changes from one cylinder and another one in one some-cylinder motor might lead to difference between pollutant emissions with calculated ones with assumption of homogeneous mixing. In terms of nitrogen oxide in which its formation depends heavily on local fuel-air ratio, its medium emission might be less or more than the amount considered as total fuel-air form. So, it seems that EGR fluid is able to reduce bad fuel distribution.

When EGR gas enters manifold through downstream carburetor valve, provided that EGR -gas conditions (particularly temperature and specific weight) is different from gasoline-air mixing conditions, it will certainly influence factors such as temperature, pressure, speed, mixing, and specific weight. Since initial conditions of trapped mixture have considerable effect on motor performance and pollution, it will change them.

Figure (18-3) shows changes of temperatures inside cylinder as function of various EGR temperatures at 2500 rpm. As it can be seen from this figure, when EGR does not exist, maximum temperature inside combustion chamber enters up to 2560K. While EGR enters, maximum temperature reduces and this reduction is high when EGR percentage is high and its temperature is low. Like for instance, maximum combustion temperature is 2417 K (5.58% reduction) with 10-percent EGR with temperature of 350 K but when the same amount of EGR with 650K is taken into account, the maximum temperature of combustion chamber will be 2427 K (reduces by 5.2%). This is mainly because N_2 has the highest amount in EGR after CO_2 and H_2O. Because this type has high specific heat in fixed volume (C_V), it will absorb more heat in combustion chamber in order to reach balanced temperature. Thus, when EGR temperature is low, more heat will be absorbed from gases inside combustion chamber.

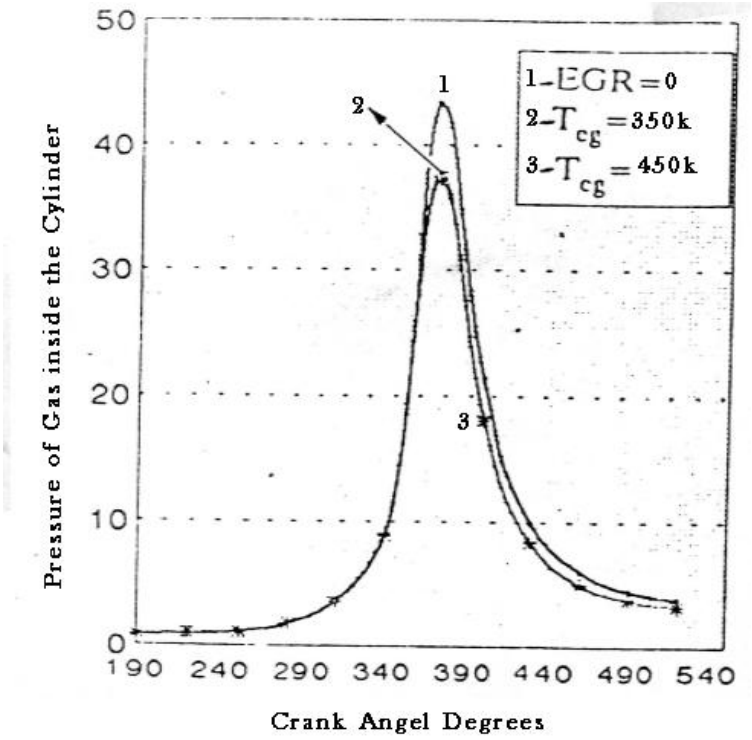


The effect of EGR-temperature changes on temperature of gases inside combustion chamber at 2500 rpm

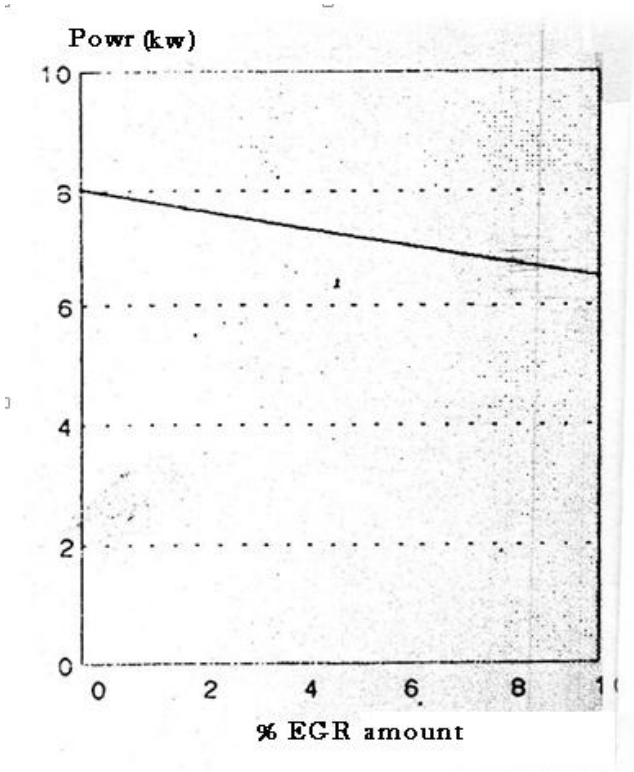
Pressure Changes of Gases inside Cylinder based on EGR Temperature

The following picture shows pressure changes of gases inside cylinder based on various EGR temperatures. As it can be seen from the figure, maximum pressure of combustion chamber, when EGR=0, rises up to 43.3^{atm}; however, when EGR is used, the pressure inside combustion chamber also falls and this reduction is high when EGR temperature rises.

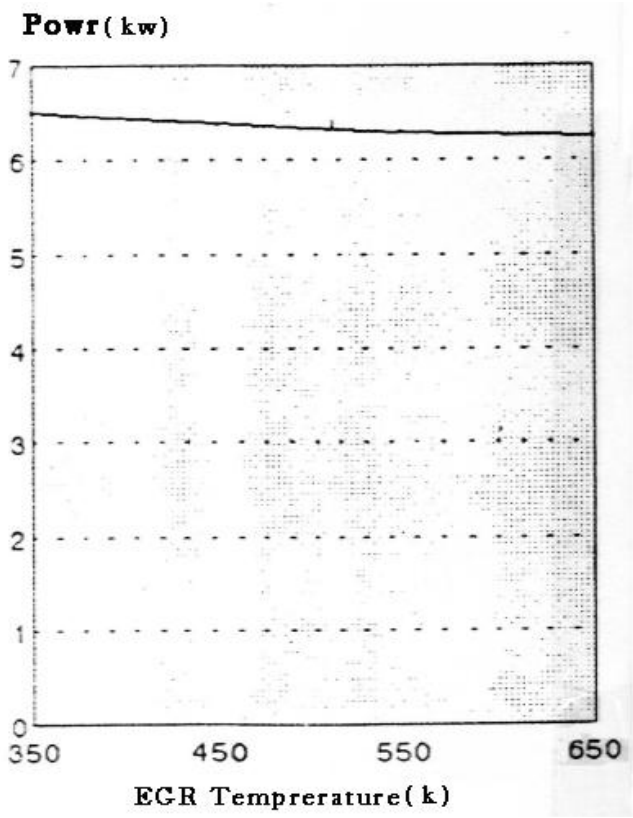
For example, EGR percentage with 350-K temperature is used, maximum pressure of combustion chamber will be 37.8 ^{atm}.(12.7% reduction) while the same amount of EGR with 450-K temperature will lead to 137.1 ^{atm} maximum pressure inside combustion chamber (14.3 % reduction). This condition is because of reduced motor volume efficiency. Since increased EGR temperature leads to mixture-temperature increase inside air manifold, its mass decreases due to increased mixture volume. As it is clear, falling pressure will have direct effect on reduced motor power.



Pressure changes of gases inside cylinder as function of EGR -gas temperature at 2500 rpm
The effect of EGR amount and temperature on motor power has been shown in Figures 21-3 and 22-3. As it is obvious from these figures, when EGR amount and temperature are high, reduced motor power will also be high.



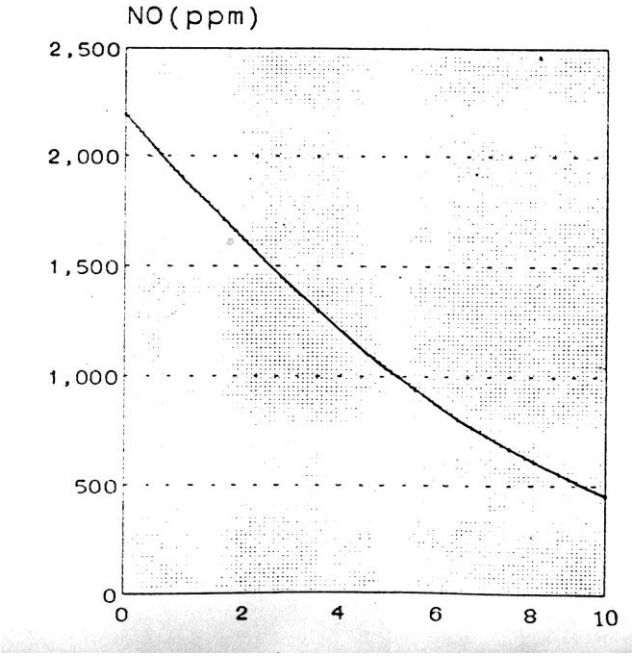
The effect of EGR amount on motor power (N=2500 rpm and tag=350^{K})



The effect of EGR temperature on motor power (N=2500 rpm, EGR =10%)

NO-concentration Changes in various EGR Temperatures

The above figure shows NO concentration as a function of EGR amount at 350 K. As it can be seen from this figure, NO concentration falls as much as EGR gas amount increase (Benson, 2014).



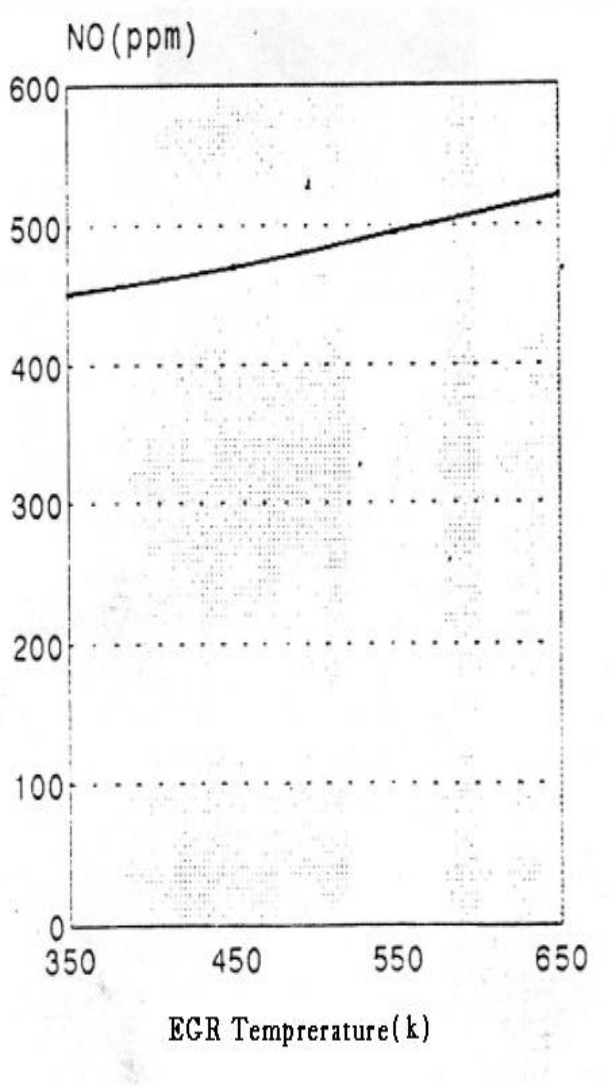
The effect of EGR amount on NO pollutant

Also, Figure 24-3 shows NO-concentration changes according to EGR temperatures. As it can be obviously seen, when EGR fluid temperature is high, NO-pollutant emission is also high. For instance, when 10-percent EGR with 350-K temperature enters, NO-concentration reduction has been 451 PPM (82% reduction) but when the same amount of EGR enters with 650-K temperature, NO-concentration reduction will be 520 ppm (79% reduction).

Furthermore, EGR gas has high speed at entrance to carburetor which can have positive effect on fuel powdering because the fuel that exits nozzl becomes tiny drops as a result of collision to pure air passing venturi and has high speed. The diameter of such drops is between 0.1 to 0.25 mm (Although some more coarse drops might be produced).

The Effect of EGR Temperature on NO Pollutant

Because fuel drops are heavier than air level, theycannot follow air flow and they might collide manifoldwalls and remain there which will be evaporated later on. Studies have shown that drops with lower-than-0.01 mm diameter can follow air flow and drops with greater-than-0.025 mm diameter will collidemanifoldwalls. The higher the air speed is, the smaller the drop diameters will be and big proportion of these drops will be carried by air flow. So, higher EGR speed will lead to increased tiny fuel drops. On the other hand, high EGR temperature leads to evaporation of fuel particles in air manifold, resulting in reduced volume efficiency of motor. It will be better to control EGR temperature to prevent reduced volume efficiency of motor.



Conclusion

In this study, the effect of EGR-fluid temperature changes on NO pollutant and other motor-performance parameters were studied and the following important conclusions were drawn:

1- Among various methods to reduce NO pollutant, EGR method is probably the simplest, the most economic, and the most appropriate method and it has been used in this article as well.

2- Using cooled EGR fluid (80 ^{oc}) in the range of 4-9 percent leads to reduce NO pollutant by 31-71 percent, reduced power by 1.6 to 5.6 percent, increased specific consumption of brake fuel by 2.5 to 3 percent, and increased unburned hydrocarbons by 9 percent.

3- Considering the results of tests, maximum acceptable EGR temperature is test condition and in motor are 1725 ^{cc} and 430 ^{K}.

Research Recommendations

- Making automobile lighter, lowering the resistance toward motion, reducing electronic and force transfersystem.
- Making motors working with poor mixture.
- Making small and turbocharge (where weight –power ratio is decreasing).The new method to have small motors is separating oxygen and Nitrogen of the air in suction tubes by a membrane. The oxygen which needs to enter cylinder for combustion forms almost 21% of the air. To this end, cylinder volume can be made in smaller sizes. In this state, NO_X emission with almost remove.
- Making a motor working with varying cylinders. In this state, the number of working cylinders will be in accordance with necessary power of automobile. This method is currently being used in six and more cylinder motors.

Automatic Switching off in long stop. In this method, in addition to energy saving, pollutants levels falls in big and congested cities. A considerable number of researchers have recommended multi-purpose catalysts in order to reduce NO_X, CO, and UHC pollutants.

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