https://doi.org/10.33472/AFJBS.6.6.2024.842-855

African Journal of Biological Sciences

Journal homepage: http://www.afjbs.com

Research Paper Open Access

The Complications and Advancements in the Exhaust Gas Recirculation Systems Used in Automobiles

Ravinder Tonk[1], Yashpreet Singh[2], Jashanpreet Singh[3], Kanishk Poonia[4], Adarsh Kumar[5], Hardesh[6], Shikha Tuteja[7]

[1,2,3,4,5,6]Mechanical Engineering Department Chandigarh University,District: Mohali, State: Punjab-Pin -140413, Country- INDIA

[7]CSE-AI Department Chitkara University, District: Patiala, State: Punjab-Pin -140401, Country- INDIA

Article Info

Volume 6, Issue 6, May 2024

Received: 03 March 2024

Accepted: 11 April 2024

Published: 08 May 2024

doi: 10.33472/AFJBS.6.6.2024.842-855

ABSTRACT:

Exhaust Gas Recirculation is an efficient method used in an internal combustion engine to reduce emissions (NOx). With rapid increase in pollution and growing energy demand, it is needed to incorporate methods to address this environmental problem. EGR works on the principle of recirculation of the exhaust gas back to engine cylinders after processing. This technique of using the waste energy can be implemented to both, petrol and diesel engines. This paper discusses the different EGR techniques and its implementation to various engines. This paper discusses the influence of EGR in current engines to reduce emission. Different methods like Port Fuel Injection and Direct Intelligence Injection is also studied. This paper also shows the different stratification methods for EGR. It was found that the EGR method is more efficient in reducing the emissions.

Keywords: Exhaust Gas Recirculation, Internal Combustion engine, Combustion, fuel, emissions, pollution, Diesel Engine, SI Engine, NOx emission.

1. Introduction

Our insight for the future is a world full of machines and robot. But apart from this, it is also true that our future will be full of pollution and wastes if the correct steps is not taken. With growing motorization, vehicle emission is one of the major contributors to the pollution these days. A great portion of all the pollution is because of the emission from the combustion engines [1]. Many studies and research are being done to reduce these emissions. For countering this we are shifting towards the green energy and electric vehicles [2].

But for the conventional IC Engine vehicle, these emissions need to be reduced. An IC Engine produces Nitrogen Oxides, Carbon monoxides and hydrocarbons and many more pollutants, which are harmful to us. From combustion in IC engine one of the common greenhouse gas, CO_2 is generated [3]. There are different methods to reduce these emissions. Exhaust Gas Recirculation is a potential method, which is used to reduce the pollution and improve the engine's efficiency. In particular, EGR is used to reduce NO_x. NO_x emissions are formed by the oxygens and nitrogen present in the atmospheric air at the high temperature inside the engine. These gases are very harmful and can cause cardiovascular and respiratory disease. EGR works on the principle of recirculation of exhaust gas to engine's cylinders [4]. Pre-heated gas passed to engine also improves engine's efficiency. Apart from the emission reduction, EGR also has application in knock resistance in vehicles and reduce providing high-load fuel in enrichment in SI Engines. EGR is also used to improve the ignition quality of difficult-to-ignite fuels in diesel engines and improving catalysts. [5] For diesel engines, it is considered as the potential NO_x control measure. However, it has potential application in SI Engines in increasing their efficiency and reducing the emissions. However, NO_x formation is favoured by the compression engine. In compression engine, high compression and high temperature are perquisite for combustion. In EGR method, exhaust gas is recirculated and mixed with fresh air in engine. This mixture has a higher heat capacity and lowers oxygen concentration. Due to the lower concentration of oxygen in-cylinder, there is less production of NO_x. But it also hinders the combustion process due to lack of oxygen.

There are different reasons for implementing the EGR. The most important reason is that it reduces emissions and help in increasing the efficiency by providing the pre-heated gas to the inlet manifold [6-7].

Exhaust Gas Recirculation Method

To study the EGR system, consider the EGR system shown below. Engine shower above is indirect injection dual engine. In this, Trap filter is used to remove the smoke. The above figure shows that using the EGR valve and steel wood filter used for recirculation in engine [8].

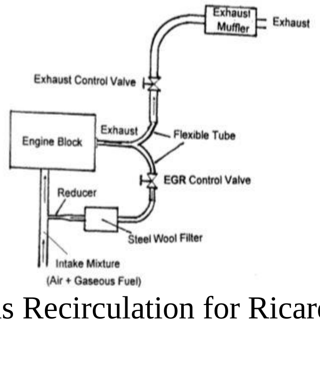

Fig.1 Exhaust Gas Recirculation for Ricardo E-6 Engine [1]

A. EGR System in diesel engines

EGR method is an efficient method for reducing the emissions. However, this method has some drawback also. In a Combustion Ignited engine (Diesel), the EGR method results in higher fuel consumption. Implementing this also result in higher particulate emissions and affects engine durability. It is also not applicable to the heavy engines as there is higher wear of piston rings. Sulfur oxide is responsible for the wearing of the pistons. From the studies, it is found that sulfur oxide concentration is inversely related to the EGR rate. It also inversely changes with the engine speed and changes under loading conditions. As the amount of CO_2 increases, the combustion noise level also increases. From another study, it was found that with combining supercharger and EGR, there is improvement in combustion and reduces emissions [8].

In the diesel engine, there is no throttling and the inlet. Thus, it can trap a large amount of air. It can trap as much as possible for it to trap in running condition. By the application of EGR, some amount of inlet air is displaced by the EGR air, shown in the figure below.

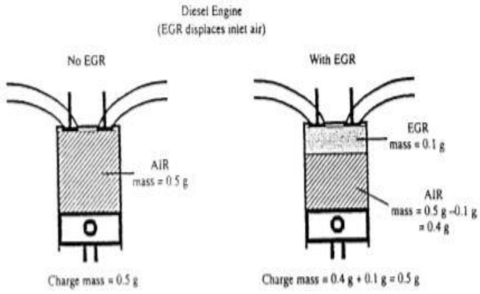

Fig.2 Diesel Engine (Inlet air displaced by EGR Air) [1]

This displacement of air results in the reduction of available air for the ignition. This changes the air-fuel ratio which results in fluctuations in engine altering the engine's performance. Oxygen presence affects the NO_x emissions and is responsible for the chemical reaction. NO_x emissions decreases by reducing the chamber oxygen (dilution effect) [9].

The result from the different studies shows that adding EGR to airflow rate of diesel engine is found to be a more beneficial way. This way resulted in exhaust emissions to reduce substantially and increased engine efficiency [10].

B. Exhaust Gas Recirculation in the SI Engines

As in the diesel engine, the EGR is effective way for controlling NO_x emissions. It also plays a primary role in SI Engine to reduce emissions. In the Petrol engine, exhaust gases is recirculated through a control valve from the exhaust to the inlet manifold. This recirculated exhaust gas is mixed with the fresh fuel-air mixture. [8]

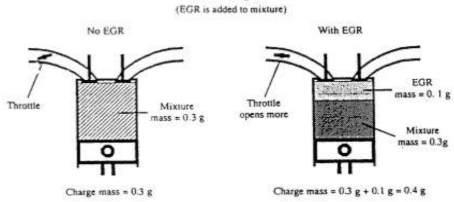

Fig.3 Gasoline Engine (Inlet air displaced by EGR Air) [1]

From studies, it was found that NO_x concentration is reduced by using EGR method and it also reduces fuel consumption and controls heat transfer between cylinder contents and surface. It was also found there is increase in HC emissions when EGR and has a very less effect on CO emissions.

From the result, it was found that in SI engines there is about 25% reduction in NO concentration. It also reduced combustion rates. The three factors which controls the fuel consumption is reduction in work done by pump, heat loss at cylinder walls, the reduction of degree of disassociation at high temperature [11].

Reformed Exhaust Gas Recirculation on SI Engine Fueled With LNG

The present concern for researchers is the growing lack of fossil fuels and the protection of the environment from the burning of these fossil fuels. We are more focused on exploring alternative fuels and to reduce the current emissions. Liquefied Nitrogen Gas has the advantage of lower sulfur and carbon emission [12]. So, because of these advantages LNG has always been under a consideration for alternate fuels in IC engine. To avoid knocking Otto cycle with lean-burn strategies is implemented t0 inhibits the NO_x emissions in LNG fueled engine. Since the CH_4 has low flame speed and the air-fuel ratio is higher it results in the misfire and unburned hydrocarbon which further results in the increase CO emission [13-15]. However, from different studies, it was found that hydrogen has unique characteristics of reduced ignition energy and increased flame speed. Imparting the Hydrogen-rich gas to the engine will increase the efficiency to a certain limit and will also result in a reduction in emission to a great extent [16-20]. Different Researches are being done in Reformed Exhaust gas Recirculation (REGR) [14]. Fig. 3 below shows the REGR system. Reformer is used to enhance to improve the property of the exhaust gas. Catalyst is used to reform exhaust gas into the hydrogen-rich mixture for stable lean burning can be achieved. From previous studies, it was found that REGR is effective in increasing engine efficiency and reducing emissions [15-17].

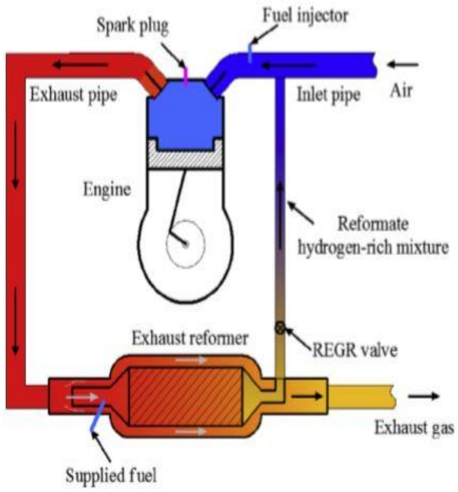

Fig. 4- Reformed Exhaust Gas Recirculation [2]

A numerical analysis was done to analyze the effects of REGR. [2] A four-cylinder engine was used. For numerical analysis k-ε (Re-normalization group) turbulence model was used. Fig. 4 and 5 below shows the computational grid and the representation diagram of flow exchanges. SAGE chemistry solver was used for combustion modelling. [18]

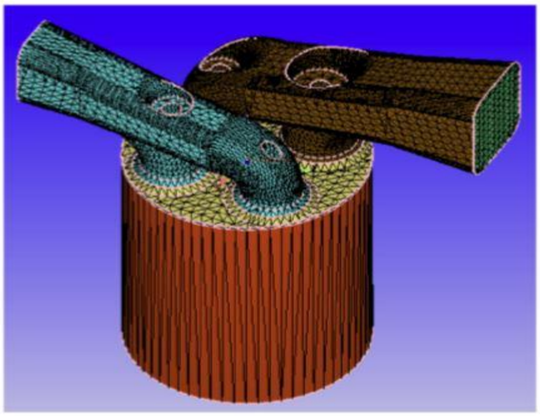

Fig. 5 Computational Grid [2]

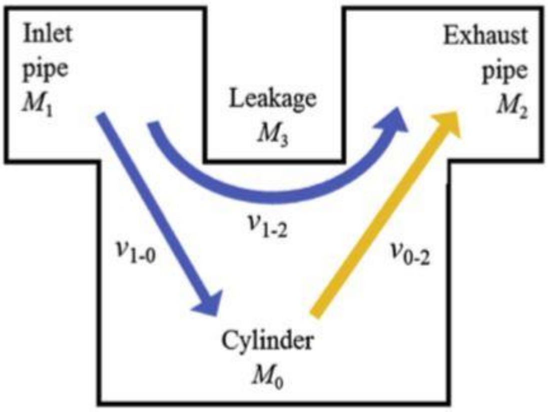

Fig. 6 Flow Exchangers [2]

After all the initial computation the model validation was done. Comparison of rate of pressure and heat release between simulations and experiments is shown in figure 6.

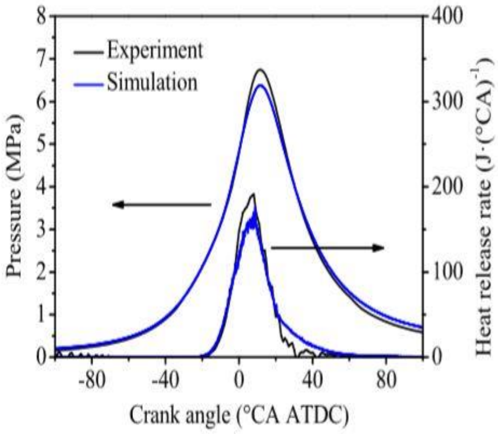

Fig.7 Results from Model Validation [18]

From this study, it was found that by implementing REGR both the concentration of left CH_4 in the cylinder and the leaking CH_4 decreases. Overall the hydrocarbon emissions decrease due to this effect. While CO emission increased by implementing REGR. As the rate of reformation or reformate increases the CO emission also increases. However, CO concentration from incomplete oxidation of CH_4 doesn't change, while CO from unburnt reformate increases. The CO from unburned reformate was the main source of CO emissions. As the Exhaust valve timing delays leaking of CH_4 and CO increases. However, the mass of unburned CH_4 and CO decreases [19]. Further, it was found that by implementing REGR with low CO in reformate and a short valve duration can lead to decrease in CH_4 and CO emissions to a great extent [20].

Reformed Exhaust Gas Recirculation in Methanol Fueled SI Engines

Methanol (CH_3OH) is always been a favoured fuel for SI engines because of its greater octane number, greater heat of vaporization and greater laminar speed. Methanol is the simplest type of liquid synthetic fuel. It is easier to produce than that of other complex fuels [18-20]. In methanol, there is no C-C chemical bond which results in soot-free combustion. There are other fuels like dimethyl carbonate and methyl-formate which produces soot-free combustion [21]. From different studies, it was found that methanol is a effective fuel for improving efficiency and controlling emissions [22-24].

Two studies on the REGR concept with methanol was done [18].

First, an Otto cycle calculation was done with approximation to get the initial idea of the impact of REGR. In this, the methodology of Szybist et al. [25] for computing efficiency using the extracted work and fuel energy was done.

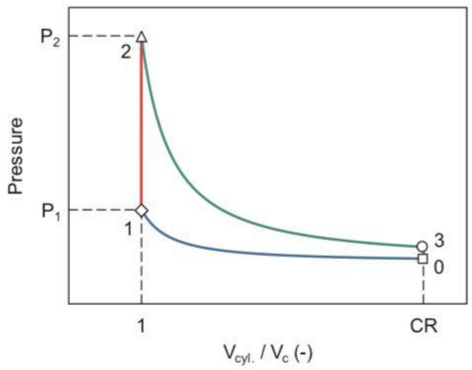

Fig. 8 P-V Diagram of Otto Cycle [18]

The Enclosed surface in the graph is mean effective pressure. First, the study was done at the ideal condition and then all the ideal conditions were removed. Study on Volvo T3 engine was done. After the results of different conditions were considered [26-28]. The Otto cycle efficiency as the reforming fraction is represented in figure9. It is was found that efficiency increases with increase in reforming fraction, although the cycle work decreases. Reforming increases the Otto cycle efficiency.

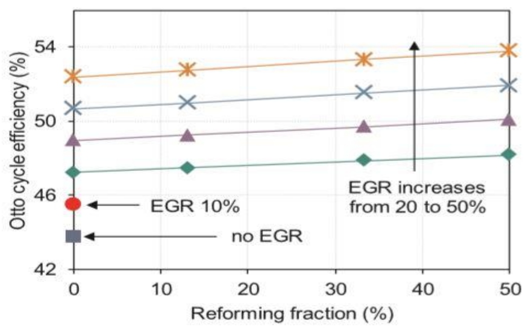

Fig. 9 Otto Cycle Efficiency with different Reforming Fraction [18]

After the theoretical study Full engine cycle simulation was done. Brake thermal efficiency can be evaluated by simulation of combustion process, heat transfer and fuel evaporation. The study [22] on Volvo T3 engine was done. Engine model was created step-by-step. [29-30]

Inlet and exhaust conditions were added with proper dimension. Calibrations of exhaust and inlet pressure profiles were used to consider the gas dynamic model. For the R-EGR engine simulation, a high-pressure EGR system was added to the calibrated engine as it provides the higher gas temperature. [32-33]The reformer was kept inside the EGR loop. For the reforming process, a simple surface reaction mechanism was used. [34] The reaction mechanism consist of reforming using methanol steam, reverse water gas shift and water gas shift reactions. After the mechanism validation and implementation were done to full engine model, a low-pressure injector was added to EGR loop, 300 mm upstream of the reformer. Fig. 10 shows the relation between EGR ratio and thermal efficiency and brake thermal efficiency [35-38].

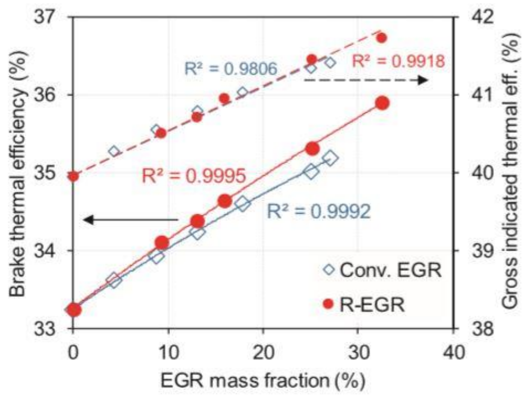

Fig. 10 Relation between EGR ration and Brake and Gross thermal efficiency [18]

It was found that methanol is easy to reform. After both the studies it was found that higher temperatures and lower pressure were produced in combustion in case of R-EGR than that of conventional EGR. There was a decrease in the cycle work when there was an increase in the EGR levels and reforming fractions. E-EGR has higher heat loss than that of conventional EGR. Combustion in case of R-EGR has more heat release than that of conventional EGR. [37]

Gasoline EGR System

EGR can be of two type vis-à-vis External EGR System and Internal EGR system. Mostly External EGR system is used as it is safe and reliable to use. In the external EGR system, the exhaust gas is taken from the exhaust pipe and passes through the EGR valves and after passing through EGR cooler it achieves the optimal condition and further enters the inlet manifold. EGR valve is varied according to the EGR rate [28]. In the external EGR system also there are different EGR system like central and decentral EGR system.

For an engine with multiple-cylinder, there are various parameters to define the EGR system likes homogeneous Gas circulation and distribution and good dynamic response [29].

For Centralized EGR system, the valves are at from distant from inlet valves and normally fixed at entrance of the inlet manifold. At inlet manifold, there is a device called collector which assist in improved mixing of exhaust gas and air and provides homogeneous distribution of mixture to the cylinders. While in decentralized EGR system the gas directly enters the inlet manifold [30].

Figure 11 shows the effects of EGR in volume occupancy.

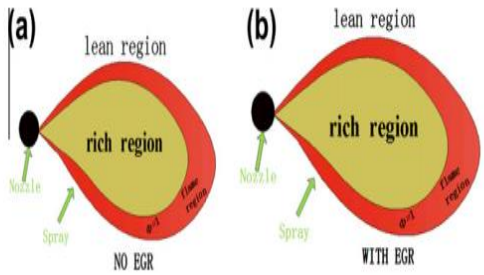

Fig. 11 Volume Occupancy by Spray Flame [30]

There are different effects of using EGR system in automobile associated with NO_X and oxygen are and the effects are shown in figure 11 below:

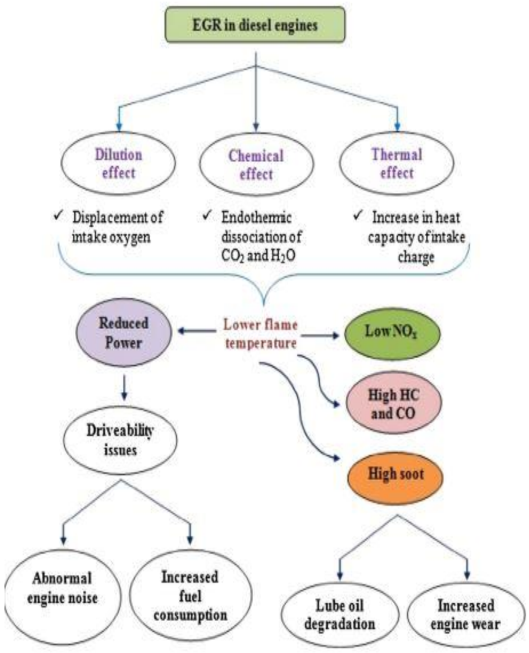

Fig. 12 EGR in Diesel Engines [28]

- Thermal Effect: There is an increase in efficiency of the combustion process as due to the entering of pre-heated gas into a manifold which further improves the efficiency.
- Dilution effect: There is the dilution in the air mixture as due to the decrease in the oxygen concentration in oxidizer and due to the decrease in highly reactive species in the combustion process.
- Chemical Effects: As oxygen is an active species for the combustion process.

There are different EGR systems for Gasoline Direct Injection System (GDI) and Port Fuel injection (PFI) system. PFI engineers are meant to work under the stoichiometric conditions and in these engines the main objective is to reduce the losses due to throttling at various

loads and further reducing the fuel consumption. Other effects of implementing the EGR are reduced emission levels. [40]
In GDI engines the EGR system resulted in a huge reduction of emissions and further improving the engine efficiency. Table 1 below shows the difference between the EGR system in GDI and PFI engines in terms of their working.

	EGR System for SI Engines	EGR System CI Engines
Target	Reduces Nitrogen other Emissions Reduces fuel consumption	Reduces Emissions Reduces fuel Consumption.
Max. EGR Rate	About 50% for Stratified Mode and 25% homogeneous mode.	25% for all modes
Max. Exhaust Temperature	450^o in optimal modes and 650^o in homogeneous modes	650^o
Other Effects	Good Dynamics Good Resolution Capability Good Distribution	

In SI or CI Engine, the homogeneous EGR system decreases the flame speed which further results in burning speed, increase in hydrocarbons emission and difficulty in achieving the steady-state combustion. Hence, highly diluted EGR charge is used to separate air/fuel mixture. Stratification in EGR is achieved by separating the EGR air and fresh air and supplying them directly in the combustion chamber. Figure 11 below shows the different stratification methods used in EGR. [42-44]

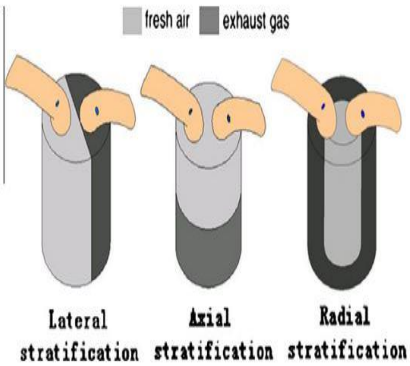

Fig. 13 Different Types of Stratification [30]

- Lateral stratification is consist of air/fuel mixture separated into two parts of cylinder. EGR at the exhaust side. However, this requires more power to maintain vertical flow momentum.
- Axial EGR Stratification is the process of horizontally dividing the whole cylinder into air zone and bottom EGR zone. There are always chances of the mixture of gases between both the zones.
- Radial EGR Stratification is the most commonly sued and reliable method as it provides the most efficient flow path for different strokes. In this, the central air duel cylinder and outer EGR tubular cylinder are in concentric cylinder forms. In this both the EGR and the air swirls in the same direction.

In Hot EGR the exhaust is directly mixed in inlet and in Cold EGR the exhaust gas is re-cooled to the optimal condition and then flowed to the inlet manifold. Cooled EGR has very low emissions, better compression but the cost associated with it is very high. The hot EGR system is a simple structure and has very low hydrocarbon emissions.[45] In the revolution of the engine, EGR was firstly introduced to control emissions and improve the engine's efficiency.

With the recent development and advancements, we have seen tremendous growth in terms of downsized engine and turbocharged engine. Implementation of EGR in the turbocharged engine is complex as it creates the coexistence in engines. For implementing EGR to the turbocharged engine other equipments and series of steps need to be followed. Figure 14 below shows the EGR implementation in a turbocharged engine. [46]

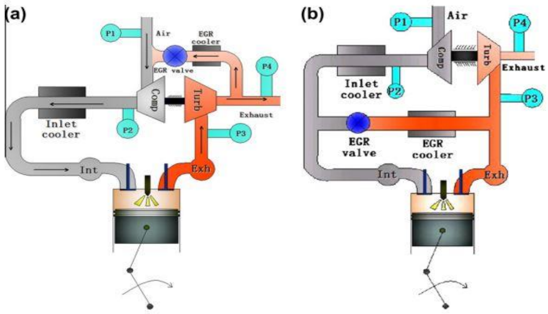

Fig. 14 Low-Pressure Loop EGR and High-Pressure Loop EGR [30]

In this process of implementing EGR to the turbocharged engine, the exhaust gas first goes to the turbine and after passing from turbine it moves to the compressor and in the compressor, the mixture of gas and fresh air is made. The pressure difference is created between the turbine outlet and the compressor inlet. Further to maintain the flow optimal a high amount of permeability is required for the EGR valve and EGR cooler. The high permeability of the valve and cooler ensures the efficiency and proper working of the compressor. If this is not maintained, it will cause overheating of intake and further reducing the efficiency. There are further implications of using these as recirculating the exhaust into the intake at high temperature may cause the corrosion to compressor and inter-cooler. [46-57]

2. Conclusion

From all the studies it was found that implementing EGR and R-EGR has helped in reducing the emissions. For Diesel Engine it was found that instead of displacing air at the inlet, adding the EGR to air-flow rate to the diesel engines[58-59]. This will result in a decrease in the emission of NO_x and CO emissions. However, in SI engine EGR reduces the combustion rate and because of this, it becomes very difficult to achieve stable combustion. EGR increases CO and Hydrocarbon emissions. From different studies, it was found that about 70% of has recycling occurred. Further, it was found that Internal and External EGR assisted in promoting and achieving the homogeneous mixture formation. It was found that lower EGR helped in achieving fewer emissions however, more soot, CO and HCs are generated. These factors lead to engine wear. Further EGR in turbocharged engine found to be improving the efficiency of the engine and reducing the emissions to a great extent.

3. References

1. G. H. Abd-Alla, “Using exhaust gas recirculation in internal combustion engines: A review,” Energy Convers. Manag., vol. 43, no. 8, pp. 1027–1042, 2002.
2. Y. Long, G. Li, Z. Zhang, J. Liang, L. Mao, and Y. Li, “Effects of reformed exhaust gas recirculation on the HC and CO emissions of a spark-ignition engine fueled with LNG,” Int. J. Hydrogen Energy, vol. 43, no. 45, pp. 21070–21078, 2018.
3. Æsøy V, Einang PM, Stenersen D, Hennie E, Valberg I. LNG- fuelled engines and fuel systems for medium-speed engines in maritime applications. SAE technical paper 2011-01-1998. 2011.
4. Korakianitis T, Namasivayam AM, Crookes RJ. Natural-gas fueled spark-ignition (SI) and compression-ignition (CI) engine performance and emissions. Prog Energy Combust Sci 2011;37(1):89e112.
5. Ma F, Wang M, Jiang L, Chen R, Deng J, Naeve N, et al. Performance and emission characteristics of a turbocharged CNG engine fueled by hydrogen-enriched compressed natural gas with high hydrogen ratio. Int J Hydrogen Energy 2010;35(12):6438e47.
6. Ma F, Wang Y, Liu H, Li Y, Wang J, Zhao S. Experimental study on thermal efficiency and emission characteristics of a lean-burn hydrogen-enriched natural gas engine. Int J Hydrogen Energy 2007;32(18):5067e75.
7. Fayaz H, Saidur R, Razali N, Anuar FS, Saleman AR, Islam MR. An overview of hydrogen as a vehicle fuel. Renew Sustain Energy Rev 2012;16(8):5511e28.
8. Ma F, Wang M, Jiang L, Deng J, Chen R, Naeve N, et al. Performance and emission characteristics of a turbocharged spark-ignition hydrogen-enriched compressed natural gas engine under wide-open throttle operating conditions. Int J Hydrogen Energy 2010;35(22):12502e9.
9. Ac¸ıkg€oz B, Celik C, Soyhan HS, G€okalp B, Karaba?g B. Emission characteristics of an hydrogeneCH4 fuelled spark ignition engine. Fuel 2015;159:298e307.
10. Zhang Z, Li G, Ouyang L, Pan Z, You F, Gao X. Experimental determination of laminar burning velocities and Markstein lengths for 75% hydrous-ethanol, hydrogen and air gaseous mixtures. Int J Hydrogen Energy 2011;36(20):13194e206.
11. Hu E, Huang Z, Liu B, Zheng J, Gu X, Huang B. Experimental investigation on performance and emissions of a spark-ignition engine fuelled with natural gas hydrogen blends combined with EGR. Int J Hydrogen Energy 2009;34(1):528e39.
12. Leung P, Tsolakis A, Rodrı´guez-Fern?andez J, Golunski S. Raising the fuel heating value and recovering exhaust heat by on-board oxidative reforming of bioethanol. Energy Environ Sci 2010;3(6):780e8.
13. Tsolakis A, Megaritis A, Yap D. Application of exhaust gas fuel reforming in diesel and homogeneous charge compression ignition (HCCI) engines fuelled with biofuels. Energy 2008;33(3):462e70.
14. Li G, Zhang Z, You F, Pan Z, Zhang X, Dong J, et al. A novel strategy for hydrous-ethanol utilization: demonstration of a spark-ignition engine fueled with hydrogen-rich fuel from an onboard ethanol/steam reformer. Int J Hydrogen Energy 2013;38(14):5936e48.
15. Tartakovsky L, Sheintuch M. Fuel reforming in internal combustion engines. Prog Energy Combust 2018;67:88e114.
16. Zheng Z, Liu C, Zhang X. Numerical study of the effects of reformed exhaust gas recirculation (REGR) on dimethyl ether HCCI combustion. Int J Hydrogen Energy 2014;39(15):8106e17.

17. Poran A, Tartakovsky L. Influence of methanol reformate injection strategy on performance, available exhaust gas enthalpy and emissions of a direct-injection spark-ignition engine. Int J Hydrogen Energy 2017;42(23):15652e68.
18. D. K. Nguyen, L. Sileghem, and S. Verhelst, "Exploring the potential of reformed-exhaust gas recirculation (R-EGR) for increased efficiency of methanol fueled SI engines," Fuel, vol. 236, no. September 2018, pp. 778–791, 2019.
19. De Cesare M, Cavina N, Paiano L. Technology comparison for spark-ignition engines of the new generation. SAE Int J Engines 2017;10:2513–34.
20. Caton JA. Implications of fuel selection for an SI engine: results from the first and second laws of thermodynamics. Fuel 2010;89(11):3157–66.
21. Szybist JP, Chakravarthy K, Daw CS. Analysis of the impact of selected fuel thermochemical properties on internal combustion engine efficiency. Energy Fuels 2012;26(5):2798–810
22. Westerhoff M. Sustainable mobility requires synthetic fuels. MTZ Worldwide 2017;78(5):8–15.
23. Hentschel L, Michels K, Garbe T, Hönig M. E-fuels – a central module for future engine design? InternationalerMotorenkongress 2018 2018. p. 487–9.
24. McCormick RL, Fioroni GM, Ratcliff MA, Grout RW, Szybist JP, Mueller C, et al., Fuel Property Characterization and Prediction. In: Vehicle Technologies Office (VTO) Annual Merit Review and Peer Evaluation; 2017.
25. Backhaus R. Alternative fuels CO2–neutral into the future. MTZ Worldwide 2017;78(6):8–13.
26. Härtl M, Stadler A, Backes F, Wachtmeister G, Jacob E. Potentially CO2–neutral fuels for clean SI engines. MTZ Worldwide 2017;78(7–8):76–83.
27. Bardin ME, Ivanov EV, Nilsson EJ, Vinokurov VA, Konnov AA. Laminar burning velocities of dimethyl carbonate with air. Energy Fuels 2013;27(9):5513–7.
28. Ranzi E, Frassoldati A, Grana R, Cuoci A, Faravelli T, Kelley A, Law C. Hierarchical and comparative kinetic modelling of laminar flame speeds of hydrocarbon and oxygenated fuels. Prog Energy Combust Sci 2012;38(4):468–501.
29. Wei, Haiqiao, Tianyu Zhu, Gequn Shu, Linlin Tan, and Yuesen Wang. "Gasoline engine exhaust gas recirculation–a review." Applied energy 99 (2012): 534-544.
30. Fontana G, Galloni E. Variable valve timing for fuel economy improvement in a small spark-ignition engine. Appl Energy 2009;86:96–105
31. Thangaraja, J., and C. Kannan. "Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels-A review." Applied Energy 180 (2016): 169-184.
32. Bai Yun-long, Wang⁄ Zhi, Wang Jian-xin. Part-load characteristics of direct injection spark ignition engine using exhaust gas trap. Appl Energy 2010;87:2640–6
33. Zhao Fuquan, Harrington David L, Lai Ming-Chia. Automotive gasoline direct-injection engines. SAE book; 2002.
34. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z. The dilution, chemical and thermal effects of exhaust gas recirculation on diesel engine emission-part 4: effect of carbon dioxide and water vapour. SAE paper 971660; 1997.
35. Agarwal Deepak, Singh Shrawan Kumar, Agarwal Avinash Kumar. Effect of Exhaust Gas Recirculation (EGR) on performance, emission, deposits and durability of a constant speed compression ignition engine. Appl Energy 2011;88:2900–7.
36. Vianna JN de S, Reis A do V, Oliveira AB de S. Reduction of pollutants emission on SI engines – accomplishments with efficiency increase. ABCM; 2005
37. Lavoie GA, Heywood JB, Keck JC. Experimental and theoretical study of nitric oxide formation in internal combustion engines. Combust SciTechnol 1970;1:313–26.

38. Ghazikhani/ M, Feyz ME, Joharchi A. Experimental investigation of the exhaust gas recirculation effects on irreversibility and brake specific fuel consumption of indirect injection diesel engines. ApplThermEng 2010;30:1711
39. Al-Qurashi Khalid, Lueking Angela D, Boehman André L. The deconvolution of the thermal, dilution, and chemical effects of exhaust gas recirculation (EGR) on the reactivity of engine and flame soot. Combust Flame 2011;158:1696–704.
40. Ladommatos N, Abdelhalim SM, Zhao H, Hu Z. The effects of carbon dioxide in exhaust gas recirculation on diesel engine emission. Proc Inst MechEng Part D – J AutomEng 1998;212:25–42.
41. Sasaki S. Effects of EGR on direct injection gasoline combustion. J Am SocEchocardiogr 1997;971:333–6.
42. Huang Bin, Hu Erjiang, Huang/ Zuohua, Zheng Jianjun, Liu Bing, Jiang Deming. Cycle-by-cycle variations in a spark ignition engine fueled with natural gas– hydrogen blends combined with EGR. Int J Hydrogen Energy 2009;34:8405–14
43. Xu Min, Chen Grant, Daniels Chao, Dong Mike. Numerical Study on Swirl-Type High-Dilution Stratified EGR Combustion System. SAE paper 2000-01-1949; 2000.
44. Dong Mike, Chen Grant, Xu Min, Daniels Chao. A preliminary CFD investigation of in-cylinder stratified EGR for spark ignition engines. SAE paper 2002-01- 1734; 2002
45. Li Zhaowen, Shu Gequn, Wei Haiqiao, Liang Xingyu. Experimental investigation on effect of EGR on combustion noise in transient conditions of DI – diesel engine. Chinese Int Combust Engine Eng 2010;31:17
46. Wei Haiqiao, Liang Xingyu, Shu Gequn. Influence of the accelerating operation mechanism on the combustion noise in DI – diesel engines. Int J Automotive Technol 2012;13:373–88
47. Najafi G, Ghobadian B, Tavakoli T, et al. Performance and exhaust emissions of a gasoline engine with ethanol blended gasoline fuels using artificial neural network. Appl Energy 2009;86:630–9.
48. Suh Hyun Kyu. Investigations of multiple injection strategies for the improvement of combustion and exhaust emissions characteristics in a low compression ratio engine. Appl Energy 2011;88:5013–9.
49. Lee DaeHee, Lee Jun Sik, Park Jae Suk. Effects of secondary combustion on efficiencies and emission reduction in the diesel engine exhaust heat recovery system. Appl Energy 2010;87:1716–21.
50. Fontana G, Galloni E. Experimental analysis of a spark-ignition engine using exhaust gas recycle at WOT operation. Appl Energy 2010;87:2187–93.
51. FathiMorteza, Saray R Khoshbakhti, Checkel M David. The influence of Exhaust Gas Recirculation (EGR) on combustion and emissions of n-heptane/natural gas fueled Homogeneous Charge Compression Ignition (HCCI) engines. Appl Energy 2011;88:4719–24.
52. Kaiser Michele, Krueger Uwe, Harris Roderick, Cruff Luke. Doing more with less – the fuel economy benefits of cooled egr on a direct injected spark ignited boosted engine. SAE paper 2010-01-0589; 2010.
53. Abd-Alla GH. Using exhaust gas recirculation in internal combustion engines: a review. Energy Convers Manage 2002;43:1027–42.
54. SarikocFatih, Kettner Maurice, Velji Amin, Spicher Ulrich. Potential of reducing the NOX emission in a spray guided DI gasoline engine by stratified exhaust gas recirculation (EGR). SAE paper 2006-01-1261; 2006.
55. Agarwal Deepak, Singh Shrawan Kumar, Agarwal Avinash Kumar. Effect of Exhaust Gas Recirculation (EGR) on performance, emission, deposits and durability of a constant speed compression ignition engine. Appl Energy 2011;88:2900–7.

56. National Green Tribunal, Southern Zone Bench, Government of India.
57. Gao J, Matsumoto Y, Namba M, Nishida K. An investigation of mixture formation and in-cylinder combustion processes in direct injection diesel engines using group- hole nozzles. Int J Engine Res 2009;10:27.
58. Kukreja, V., & Sakshi. (2022). Machine learning models for mathematical symbol recognition: A stem to stern literature analysis. Multimedia Tools and Applications, 81(20), 28651-28687.
59. Kukreja, V., & Ahuja, S. (2021, September). Recognition and classification of mathematical expressions using machine learning and deep learning methods. In 2021 9th International Conference on Reliability, Infocom Technologies and Optimization (Trends and Future Directions)(ICRITO) (pp. 1-5). IEEE.