A Review on the Advances in Design of Exhaust Gas Recirculation (EGR) for Diesel Engine

Muhammad Mustafa Generous
Department of Mechanical Engineering,
King Fahd University of Petroleum & Minerals,
Kingdom of Saudi Arabia
mustafagenerous@gmail.com

Abstract: Diesel engine is one of the enormously used technologies in mobile and stationary application. Although, this enormous use boomed the economic development but it also caused serious environmental hazards. Diesel engine uses combustion phenomenon that gives birth to SO_X, NO_X, soot particles and other dangerous compounds. Exhaust Gas Recirculation (EGR) technology was developed to control the emission of NO_X. EGR technology today is not as it was a few decades ago. It evolved with the passage of time. The study of evolution in previous two and half decades is the scope of this review paper. Work on the control and sensing technology is also discussed but major scope of this paper is to review advances in EGR technology from mechanical perspective. Addition of new components along the timeline in the choronological sequence is briefly described. An effort is made to gauge the work in different areas and to direct future work to improve EGR technology.

Keywords: diesel engine, exhaust gas recirculation, soot particles, NOx, Sox

الخلاصة: محرك الديزل هو أحد التقنيات المستخدمة بكثرة في التطبيقات المتنقلة والثابتة. على الرغم من أن هذا الاستخدام الهائل ازدهرت به التنمية الاقتصادية إلا أنه تسبب أيضًا في مخاطر بيئية خطيرة. يستخدم محرك الديزل ظاهرة الاحتراق التي تولد SOX، NOX ، جزيئات السناج والمُركبات الخطرة الأخرى. تم تطوير تقنية إعادة تدوير غاز العادم (EGR) للتحكم في انبعاث NOX أكاسيد النيتروجين. تقنية EGR اليوم ليست كما كانت عليه قبل بضعة عقود. تطورت مع مرور الوقت. إن دراسة التطور خلال العقدين ونصف العقد السابقين هي نطاق ورقة المراجعة هذه. كما تتم كذلك مناقشة العمل على تكنولوجيا التحكم والاستشعار ولكن النطاق الرئيسي لهذه الورقة هو مراجعة التطورات في تكنولوجيا EGR من منظور ميكانيكي. يوصف بإيجاز إضافة مكونات جديدة على طول الخط الزمني في التسلسل الزمني. يتم بذل جهد لقياس العمل في مجالات مختلفة وتوجيه العمل المستقبلي لتحسين تكنولوجيا EGR.

1. Introduction

Ever increasing energy demand and stringent regulation to control environmental pollutants like the emission of SO_X and NO_X are pressurizing the researchers to find energy viable and environmental friendly engine emission technologies [1]. Various techniques were applied to make IC engines especially Diesel engines energy efficient. One of these was the use of turbocharger that uses exhaust from the engine to drive turbine that in turn drives the air compressor to feed air at elevated temperature to the compression ignition engine [2]

In olden times smoke out of the chimney was considered the sign of prosperity of nation and then time changed and stringent laws was imposed to bring pollutants especially SO_X , NO_X and Lead (Pb) emission from engines to acceptable concentration in order to avoid their effects on human health, property, and aesthetics of the environment [3].

Scientists and engineers around the globe targeted to control NO_X emission from internal combustion engines. Exhaust gas recirculation technology was brought into play to control mainly the NO_X emission produced during the combustion of fuel. When Air enriched with oxygen react with Nitrogen at elevated temperature due combustion flame then NO_X are produced [4].

Exhaust Gas Recirculation (EGR) system diverts a part of the exhaust to the air inlet of diesel engine to make it diluted. It causes reduction in flame temperature due to reduction in availability of oxygen and an increase in heat capacity. It creates barrier in the reaction of nitrogen and oxygen to produce NO_X. Hence, EGR is also a tool to manipulate with combustion processes like Premixed Charge Compression Ignition (PCCI), Homogeneous Charge Compression Ignition (HCCI) and Low Temperature Combustion (LTC) [5–8].

Table 1: An overview of the effects of EGR on NO_X and pollutants emission [9–11]

No.	Effects	Reason of the effect	Consequences
1	Dilution of engine intake	• Oxygen displancement form intake	• Reduced flame temperature.
2	Chemical effect	• Dissociatio of H_2O and CO_2 due to endothermic process	• Reduced power production.
3	Thermal effect	• Heat capcity increase of the intake mixture	• Increased fuel comsumption. • Engine noise • Hight soot production • High HC and CO generation. • High soot formation. • Lube oil degradation • Engine wear

Effects of Exhaust Gas Recirculation System are summarized in the Table 1. It explains that EGR technology causes dilution effect which in turn reduces flame temperature. Low flame temperature forces higher soot emission. The amount of air circulated by the Exhaust Gas Recirculation System is decided by the number of operating points set by the environmentalists to bring the emission below legislated limits.

Exhaust gas recirculation Technology was improved and evolved with passage of time to find a compromise between an acceptable NO_X emission and efficiency of the engine. Important modifications in EGR and their effectiveness will be discussed in the literature review section. Contribution of various authors is summarized in Table 2.

Novelty of this work is (a) to study evolution in EGR technology, (b) to compare the work of various authors regarding EGR, (c) various design modifications, and (d) Assessing the researches already done and suggesting future direction.

Table 2. Summary of contribution of various authors to study the impac of EGR on engine performance and emissions.

Contribution	Ref.
Agarwal et al. experimentally investigated the performance and emission for various EGR rates for direct injection diesel engines at constant speed. Hydrocarbons, NO_X, and carbon monoxide, smoke opacity and exaust gas temperatue were measured. High wear rate of piston rings and high carbon deposits were observed.	[12]
Millo et al studied various architectures of EGR system by experimental tests and 1D model. A combination of short an long route called Dual loop was evaluated. Dual loop was found to have 5% reduction in NO_X esmission.	[13]
Wei et al. studied the impact of EGR on gasoline engine and conluded that the technology can enhance fuel economy, reduces knocks and NO_X emission.	[3]
Asad et al. proposed a global equation to assess steady state and transient concentration in the exhaust.	[8]
Peng et al. investigated the impact of EGR on Direct Injection diesel engines during cold start. It was found that high EGR led to higher white smoke production. NOx emission is affected by increment in fuel intake. EGR impact on NOx reduction become significant when combustion become stable.	[14]
Hansen et al. investigated control architectures. Reference tracking and disturbance rejection are studied using model uncertainity.	[15]
Divekar et al. developed an EGR model for the quantification of interaction between oxygen intake and engine operating variable including EGR amount, intake boost, and fluel type.	[10]
Min et al. studied dual loop EGR with turbocharger for light duty diesel engines using sensors and product engines.	[16]

Jafarmadar and Nemati investigated the impact of EGR on exergy efficiency for diesel engine operating with hydrogen and diesel oil.	[17]
Chen et al. assessed the impact of EGR on heavy duty diesel engine using disesl with 40% butanol. It was concluded that EGR dramatically reduced NOx emission with no effect on soot.	[18]
Galloni et al. studied the influence of EGR on turbocharged SI engine using both numerical and experimental approach. The impact of EGR on octane requirement, engine performance, and exhaust gas temperature was studied for different roational speeds.	[19]

2. Literature review

Diesel engine was considered low emission and environmentally promising technology until 1995 when United States Environmental Protection Agency (USEPA) put stringent policy and asked the state governments to enforce emission standards. Before that secondary emission control technology such as catalytic converter was not mandatory. It was difficult to fulfill the standards without secondary emission technology after USEPA's legislation [20].

Before that only catalytic activities are used to somehow control the NO_X emission. Use of ammonia was proposed as a reducing agent to control NO_X emission. Its usage on passenger's vehicle was hardly feasible [21]. It was suggested by certain laboratories to use CO and HC in the intake to control NO_X emission. This is how this technology came into play [20].

$$4NO + 4NH_3 + O_2 \longrightarrow 4N_2 + 6HO_2$$

$$2NO_2 + 4NH_3 + O_2 \longrightarrow 3N_2 + 6HO_2$$

Exhaust Gas Recirculation (EGR) initially was a just conduit from exhaust channel to intake channel of the diesel engine [22]. EGR valve was integrated later in this conduit (Fig. 1). It reduced the oxygen nitrogen ratio in the intake and resulted in low combustion temperature and less availability of oxygen for the oxidation of Nitrogen contents of the intake in order to avoid NO_X emission. Unluckily the integration of EGR technology resulted in high emission of soot particles. Thus it was targeted by the researcher to reduce enhanced particulate concentration due to the integration of mentioned technology[23].

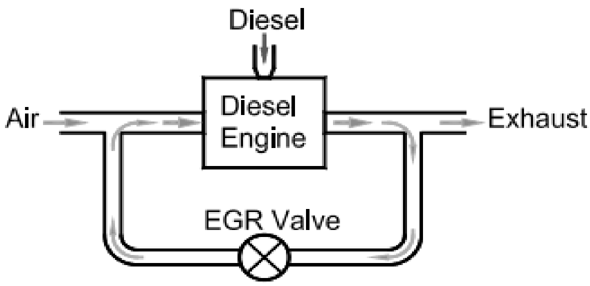

Fig.1. Exhaust Gas Recirculation (EGR) Conduit with EGR Valve.

Modeling and proportional integral derivative (PID) controller loop was investigated and control valves were integrated in the conduit that allows some of the combustion product into the intake tract of the engine. The problem in the use of this technology was that variation in pressure and EGR rate were dependent on the both variables named Turbine vane Position and Value Position (degree of openness or closeness). Problem was solved by activating only one loop while keeping other variable constant. PID controller was proved more effective than Model Predictive Control (MPC) [22]. PID was designed to change set point on the change of variables and it ultimately caused strong EGR Rate Change for optimum value. In this way the EGR was made better and effective to control the composition of the mass that was to be charged to diesel engine[24].

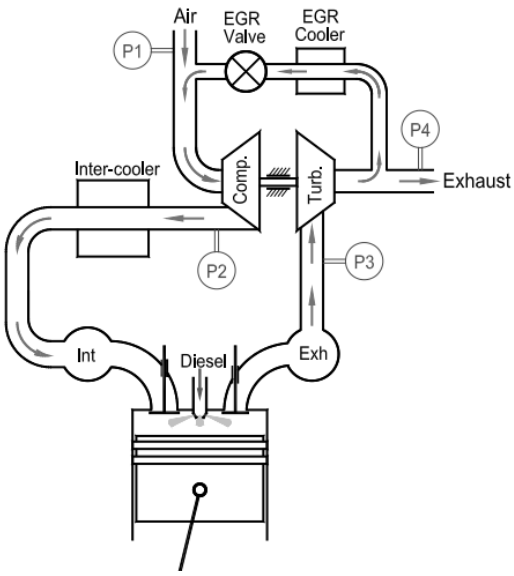

Fig. 2. Integration of Exhaust Gas Recirculation (EGR) Cooler.

The EGR technology was improved when new generation of control valves came in and accuracy was improved by electronic systems. Further, EGR cooler was used for more reduction in NO_X emission than the conventional one. Therefore Exhaust Gas Recirculation Cooler (EGR) was also integrated in to the EGR system to get the emission controlled (Fig. 2). G.H. Abd-Alla [25] used Ricardo E6 Engine and installed an EGR system. Temperature of exhaust gas was noted by inserting thermocouple in the EGR pipe near the intake manifold. Part of the EGR pipe was manufactured by using flexible stainless steel. Flexible Stainless steel was used to absorb engine vibrations those can destroy exhaust system and measuring instruments. Pipe of EGR was insulated by using Glass wool. It helps to reduce temperature drop. The schematic is shown in the Fig. 3.

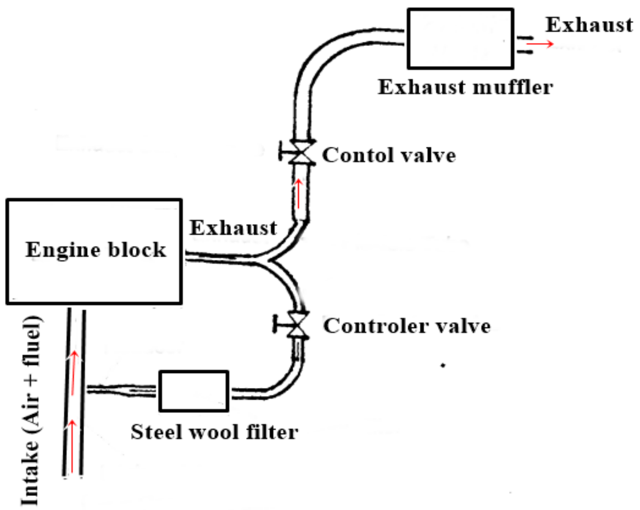

Fig.3. Exhaust Gas Recirculation (EGR) system with flexible steel pipe design for vibration control.

Inlet air was removed and equal volume of combustion products were inserted into the air intake channel. That resulted in 14% reduction in flow rate due to EGR. Some of the air is displaced by water vapors and CO_2 which are integral parts of combustion products. The application of EGR reduced N_2 flow rate by 15% and O_2 by 19%. Dilution of intake mass with exhaust increased the mass temperature that significantly affected combustion process. The effect of reduction of O_2 concentration by dilution of CO_2 , N_2 and exhaust gas was traced as shown in Fig. 4 [25].

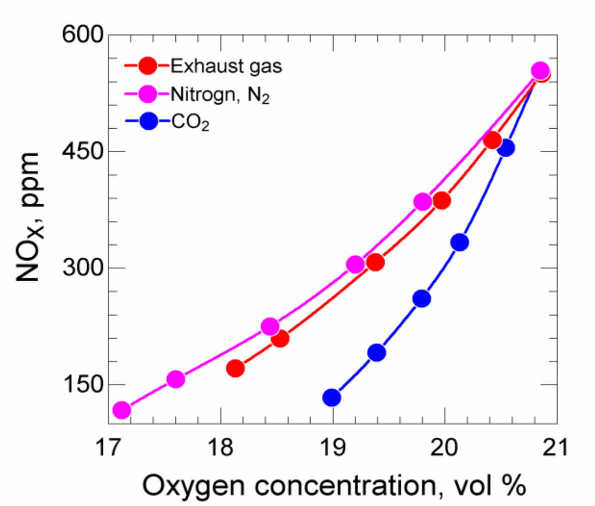

Fig.4. Effect of reduction in oxygen concentration by different diluents (EGR, CO2, N2) on NO_X emissions in diesel engine.

It was also found that the use of EGR system had several draw backs as well. Use of EGR increased specific fuel consumption and particulate emission especially at high loads. It has an adverse effect on lubricating oil quality and engine durability. The emission of CO_2 was enhanced due to this technology. However NO_X emission was reduced with the combined use of superchargers and EGR System [25].

Initially control valves along with PID were used to enhance the performance of EGR system. PID was designed to change set point on the change of variables and it ultimately caused strong EGR Rate Change for optimum value. Latter design was modified and EGR cooler was introduced along the EGR duct [26]. M. Zheng et al. [22] proposed to use a Catalytic Oxidation Box to maintain a safety margin of ash contents in 2004 (Fig. 5). It was proposed that it could make EGR more stable during inconsistencies of the operation of EGR [8].

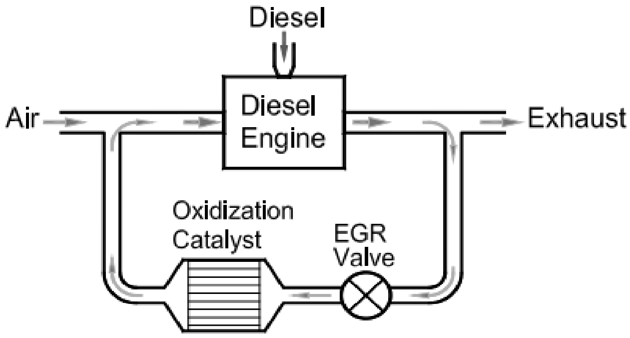

Fig.5. Catalytic Oxidation Box integration in Exhaust Gas Recirculation System.

M. Zheng et al. [22] proposed the use of EGR Reformer in the same study (Fig. 6). Reformer can be used to produce carbon mono-oxide and hydrogen so they might facilitate premixed combustion enhancement in the cylinder [22].

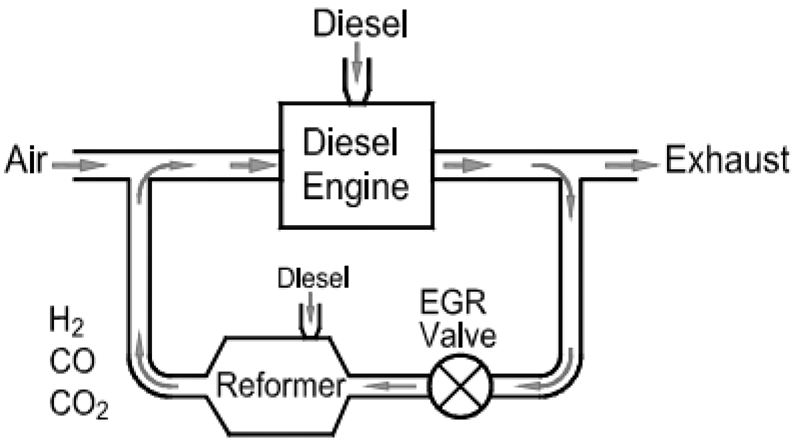

Fig.6. Integration of Reformer in Exhaust Gas Recirculation (EGR) System.

R. Moss et al. [27] tried to put sensor technology in order to measure EGR rate. Position sensor was used to determine the degree of opening of the throttle valve enabling EGR control loop. EGR control rate depends on temperature, pressure difference, intake and exhaust restrictions or exhaust gas recirculation fouling. To compensate these environmental factors direct measurement of EGR rate is mandatory. He used temperature sensor, mass flow meter and back pressure sensor to get the direct measurement of EGR as shown in the Fig. 7.

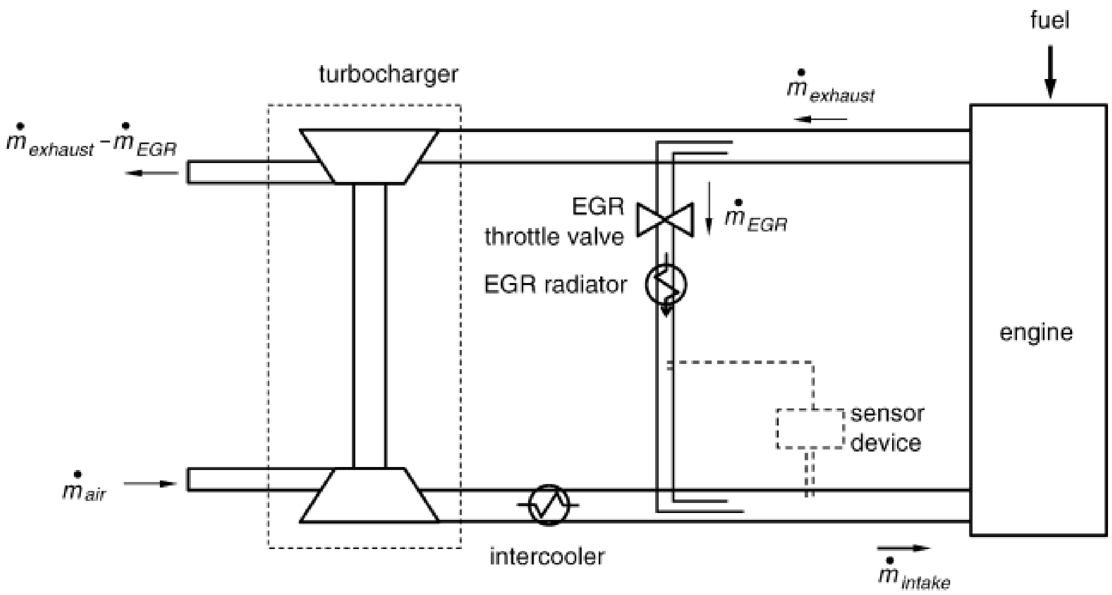

Fig. 7. Layout to put sensors in order to directly measure EGR rate.

Integration of Air Box was reported by Agarwal et al. [12] in his work in 2009. The flow of exhaust fluctuates when the exhaust is allowed to pass through Exhaust Gas Recirculation (EGR) channels. It happens due to the large pressure difference of intake air in the intake manifold and exhaust manifold. Exhaust pressure is higher due to higher temperature of exhaust as compared to fresh air. This difference in pressure caused fluctuations and turbulence in the flow of exhaust in the EGR loop. The problem was taken in to account by Agarwal et al by introducing Air Box in the EGR loop having a diaphragm as shown in the Fig. 8 below [12].

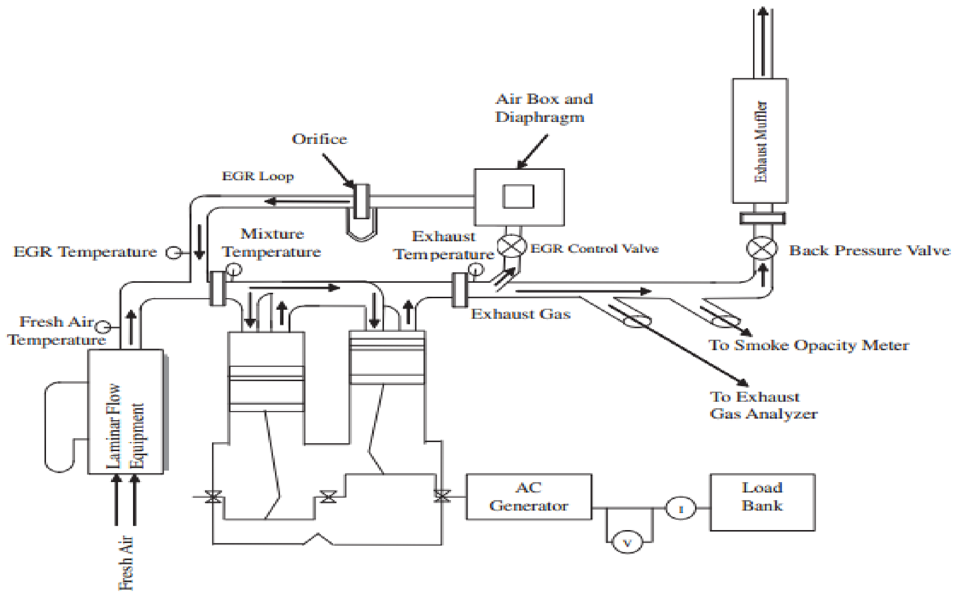

Fig.8. Air Box Technology in the Exhaust Gas Recirculation (EGR) Loop.

They used an orifice to measure flow rate and EGR temperature sensors to monitor temperature of exhaust that need to be mixed with fresh incoming air.

High Pressure or Short Route (SR) Layout and Low Pressure or Long Route (LR) Layout was discussed by F. Millo et al. [28] in 2012. They also used Diesel Particulate Filter (DPF) to capture particulate matters from the exhaust. It saves compressor damage from particulate matters as well. Both Short Route (SR) and Long Route (LR) architecture can be combined to get a mixed one or Hybrid Layout. But in that case it must have a bypass system as extremely cooled EGR can increase unburned hydrocarbons and carbon mono-oxide emission especially during start up due to combustion instability. Although, SR is preferred for vehicles but LR layout of EGR is more environmentally friendly due to integration of DPF. Both system of layout of EGR are shown in the Fig. 9 [9].

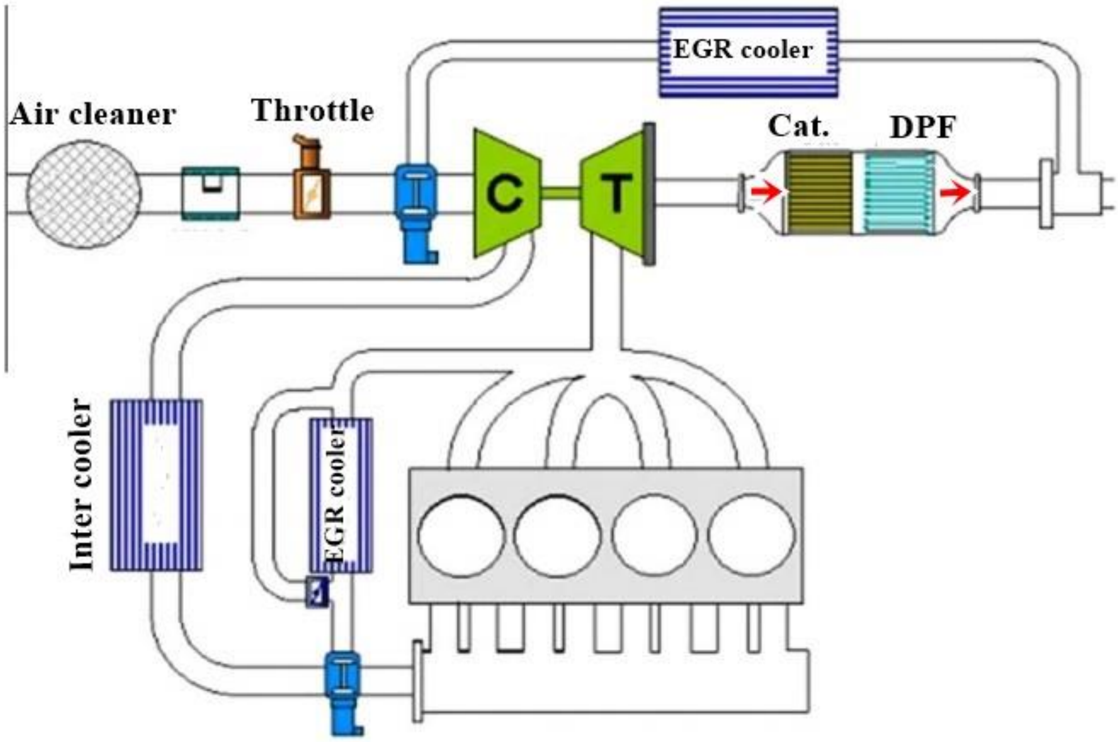

Fig.9. Short Route (SR) and Long Route (LR) Exhaust Gas Recirculation Layouts.

DPF reduces the damage to compressor wheel and charge air cooler fouling. It has the capability to hinder carbonaceous contents from the exhaust. Therefore it saves not only compressor wheel damage but also stops accumulation of these matters in the intercooler channels. Diesel Particulate Filter (DPF) also produces necessary plumbing effect in exhaust gas recirculation circuit that in turn offers optimum resistance to the flow of exhaust [28].

DPF is also called Diesel Particulate Trap (DPT). It uses different types of technology like honey comb aluminum mesh, aluminum wire mesh, and ceramic fiber technology. Honey comb mesh is the most recent technology. Regeneration process was designed to clean the filter from particulate matters. Active and passive regeneration processes are used to convert particulate matters into CO_2 without causing a damage to filter. Temperature is build up to 500 ^{0}C upon receiving a signal from particulate stack monitoring system to burn the particulate matters in the active regeneration. But now a day a passive or catalytic regeneration is preferred due to economic limitations. Catalytic oxidation is used in the passive technique to achieve the same purpose as shown in Fig. 10 [29].

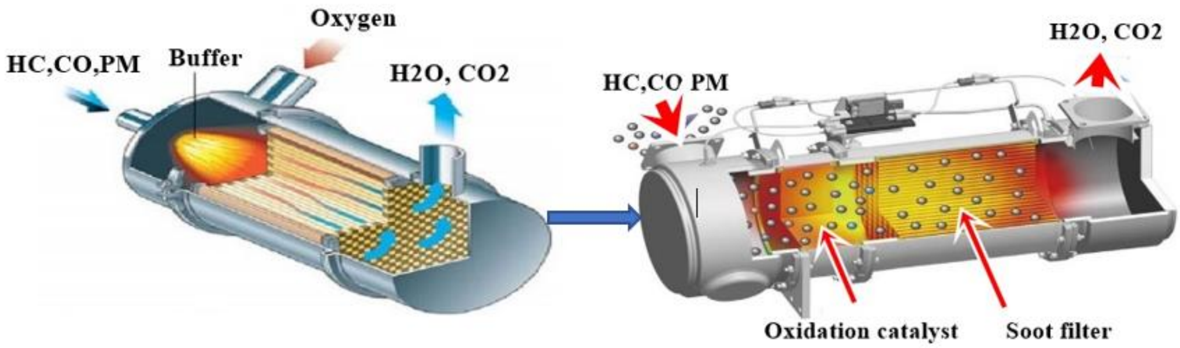

Fig.10. Advancement in Regeneration Process from Active to Passive Regeneration in DPF

F. Millo et al. [28] also studied the soot and NO_X emission for both Short and Long Route EGR systems. Schematic diagrams for both long and short route exhaust gas recirculation system are shown in Fig. 11.

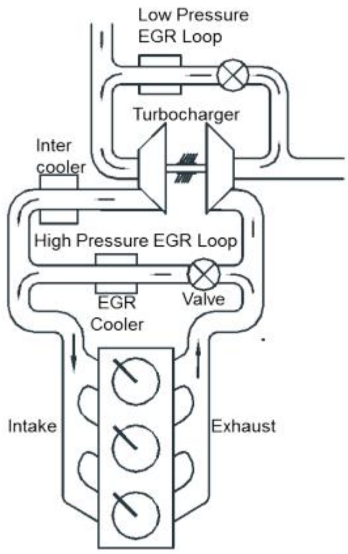

Fig.11. High Pressure and Low Pressure EGR loops in modern engines.

Mostly diesel engines in this age use High Pressure (HP) EGR while others rely on Low Pressure (LP) EGR. High Pressure EGR is prominent technology for production engines while low to moderate pressure EGR systems are used in common application. Both HP and LP EGR systems used in modern diesel engines. Their comparison with respect to soot emission is summarized in Fig. 12. Exhaust is allowed to pass first through compressor due to which it loses its temperature energy. Reduction in temperature causes reduction in pressure as well [10].

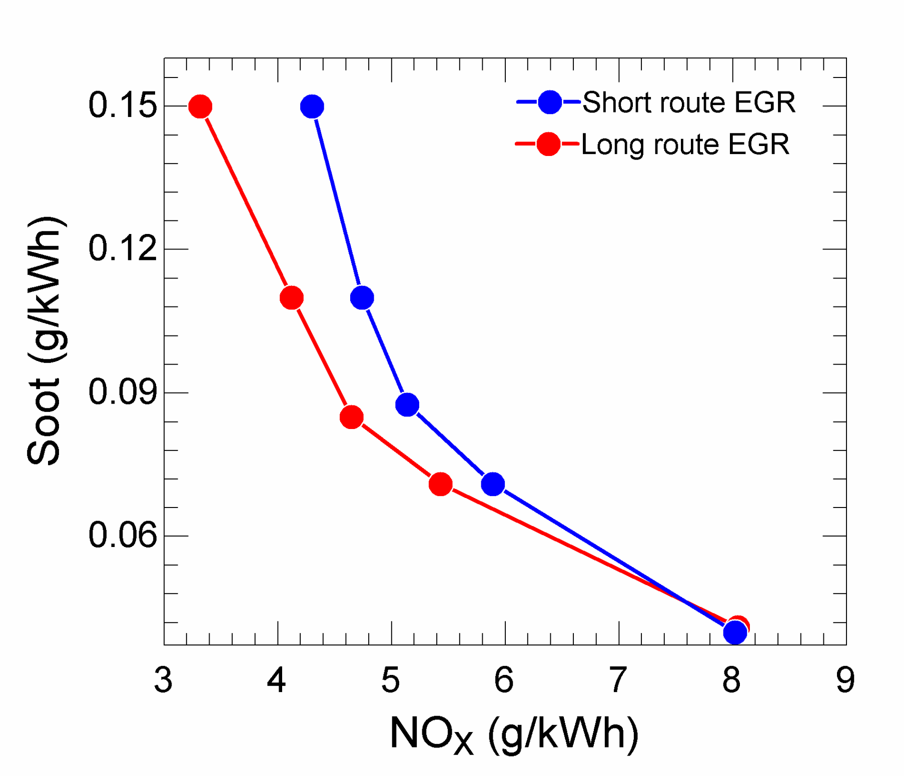

Fig.12. Soot and NO_X emission as a function of EGR rate for both short and long route EGR.

Exhaust Gas Recirculation (EGR) cooler was used by many researcher before its injection into the intake manifold of the engine. Combustion residue including soot particles, unburned hydrocarbons and their mixture is allowed to pass through the EGR cooler. Soot particles and unburned hydrocarbon deposits an insulating layer that causes a significant reduction in the thermal efficiency of EGR cooler [30] . Beside reduction in thermal efficiency, it affects intake pressure, and engine efficiency. In order to minimize these losses Janabi and Malayeri [31] investigated different design modifications in the EGR cooler. They experimentally investigated the effects of grooved plates, straight and inclined ribbed plates as shown in Fig. 13. They concluded that although ribs developed a flow separation and turbulence but have better overall thermal efficiency. Flat ribbed are particularly suitable in term of low thermal resistance as compared to other structural designs. Groove plates performance depends on the dimension of grooves that need to be investigated yet.

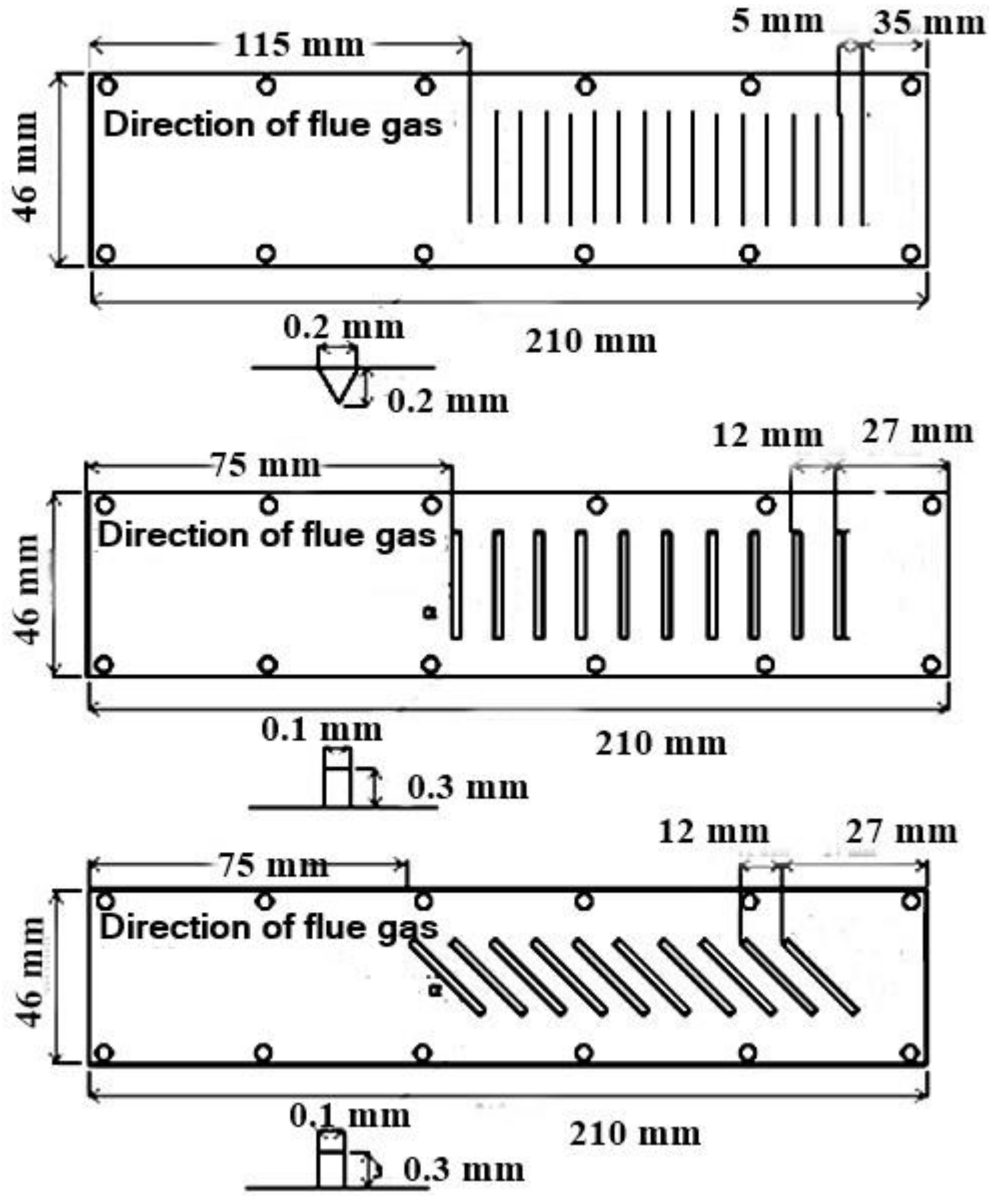

Fig.13. Design of grooved plates, straight ribbed plates, and inclined ribbed plates in the EGR cooler.

3. Summary

Exhaust Gas Recirculation (EGR) was no more than an orifice that allowed the exhaust of the engine from exhaust manifold to the intake manifold. Pressure difference was the driving force to push the exhaust from exhaust to the intake mixture. The technology evolved with the passage of time. Evolution in EGR technology with time is shown in the form of flow diagram below.

<u>EGR evolution Tree</u>

EGR Orifice
(Orifice that allowed the flow of exhaust from exhaust manifold to intake manifold)

Duct based EGR
(Duct from exhaust manifold to intake manifold)

Valve integration in EGR duct

Sensors and PID controller
(To control the composition of intake mixture)

Improvement in valve and sensors technology
(To improve accuracy)

Flexible stainless steel pipe usage for EGR duct (aluminized steel tubing/stainless steel)
(To reduce vibrations)

EGR cooler technology
(To reduce the temperature of exhaust)

Catalytic Oxidation Box Technology
(Oxidation of particulate matters)

Reformer Technology
(For premixed combustion enhancement)

EGR control loop integration
(For direct measurement of EGR Rate)
(Used flow meter, back pressure sensor, and temperature sensors)

↓

Air box technology having a diaphragm
(To minimize turbulence in the EGR channel)

↓

High pressure and low pressure EGR
(Loops)

↓

Hybrid EGR technology
(Mix of both high and low pressure EGR)

↓

Use of diesel particulate filter (DPF/DPT)
(To capture particulate matters to avoid fouling, compressor damage and others)

↓

Advance in the design of diesel particulate trap (DPT)
(Honey comb, wire mesh, ceramic fiber technology)

↓

Active and passive regeneration technology
(Coordinates with Particulate Stack Monitoring System to clean the filter in DPT)

3.1. Critical analysis and future work recommendations

EGR diverts a part of exhaust to reduce the concentration of oxygen. It is done to control the NO_X emission as limited oxygen deprive of nitrogen to oxidize. It also reduces flame temperature for combustion.

Although EGR is promising technology to reduce NO_X emission but it deteriorates engine efficiency as well. Researcher tried to find a compromise between the two. Therefore, it is desired to improve the effectiveness of EGR with minimum impact on engine efficiency. Although a lot of work was done to improve control technology to make EGR more effective but major concern of this paper is to critically review mechanical advances in EGR technology.

Beside Efficiency reduction another problem caused by the EGR technology is soot emission enhancement (Fig.14). Soot is the major source of fine suspended particle that are carcinogenic for human health. They enter human body through respiratory systems and cause damage to brain cells as reported by B. Rajesh Kumar et al. [32].

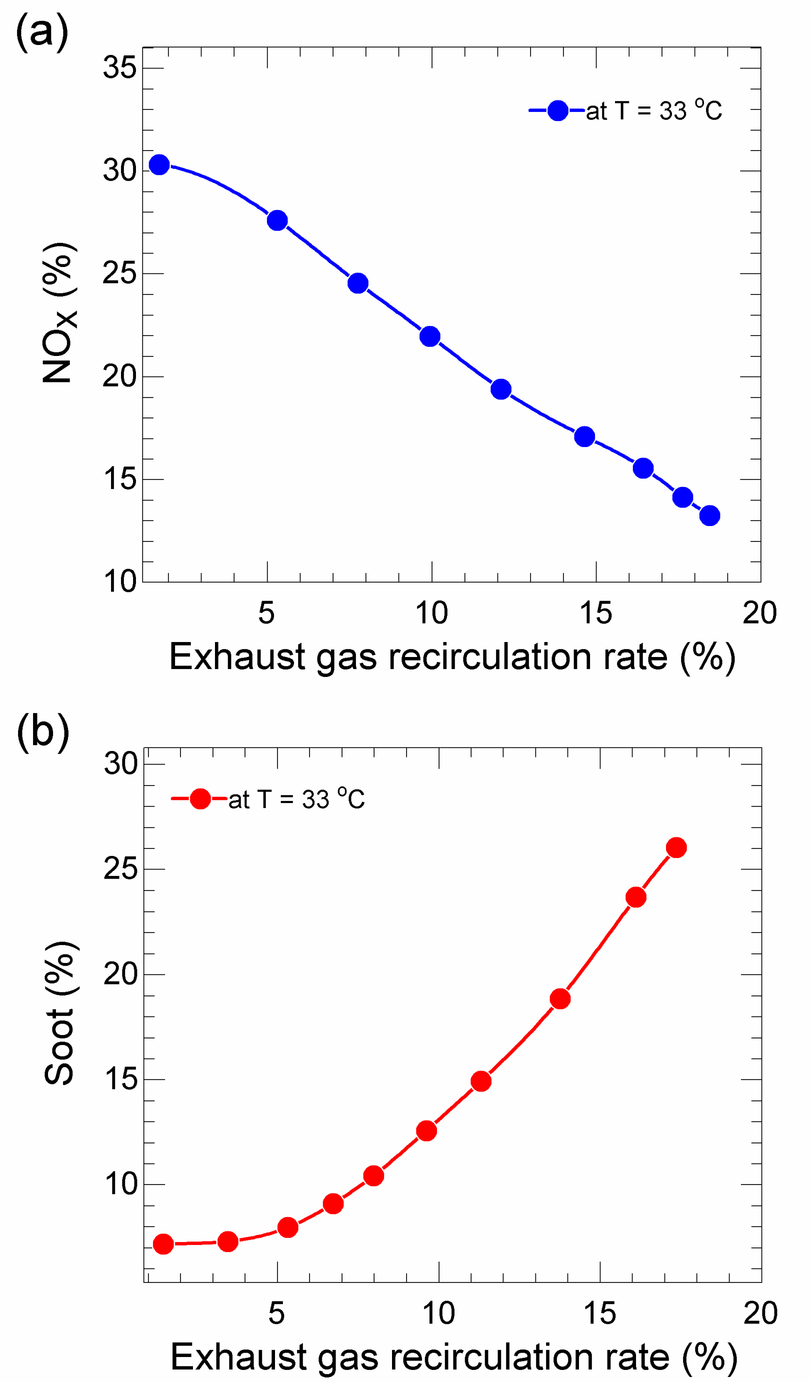

Fig.14. (a) Decreasing NO_X and (b) increasing soot emission with increasing EGR Rate [33].

Therefore, we must look for alternate fuels like biofuels as they are comparatively better option regarding energy security concerns. Efforts should be made to maximize the

utilization of other energy sources like electricity. Best advancement is hybrid cars technology that can be operated at electricity beside fossil fuels.
G.H. Abd-Alla [25] used flexible steel pipe for Exhaust Gas Recirculation System so that vibration may be controlled as vibration might be disastrous for the instruments. More research can be done in this area to find the most effective way of vibration control.

Similarly Agarwal et al. [12] reported the use of air box to control turbulence phenomenon inside EGR system. Turbulence in EGR was not studied in detail. Research is needed to study the flow of exhaust in different geometries of EGR to minimize turbulence effect.

F. Millo et al. [28] used Diesel Particulate Filter (DPF/DPT) to trap matter particulates. It is very useful technology as it will hinder most dangerous carcinogenic particles to enter in the atmosphere. But efficiency of DPF deteriorates due to blockage of wire frame like structures. It means it is to be cleaned out repetitively for good performance. Researcher needs to concentrate to improve DPF such that it does not require regular cleaning. Same is the case with fouling effect in the intercooler and EGR cooler.

Janabi and Malayeri [31] took and initiative to investigate change in the design of EGR cooler. They studied the effect of grooved plates, straight and inclined ribbed plates and preferred to use flat ribbed plates. But they have not investigated fluid dynamics of exhaust passing through holes of grooved plates and have not optimized grooved size according to flow requirement.

Similarly, ribs geometry, number of ribs, and ribs angle with the flow are all need to be investigated in detail to optimize the exhaust flow in EGR cooler with minimal thermal resistance.

4. Conclusion

This paper summarizes the evolution in the design modification in Exhaust Gas Recirculation (EGR) technology in chronological order. EGR is a technology that pushes a portion of exhaust from exhaust manifold into the intake manifold of diesel engine. This reduces oxygen availability for nitrogen to oxide and hence create barrier for production of NO_X during combustion process.

EGR causes reduction in flame temperature. Reduction in flame temperature reduces power production by IC einge. Benefits and side effects of EGR technology are discussed and various improvement in public literature are assessed. A lot of work has been done in previous few decades but more work needs to be done in certain area like DPT cleaning, intercooler design and air box design optimization to minimize turbulence in the channels of EGR. It is also proposed to carry out research to modify the geometry of EGR, may be through CFD analysis, to minimize resistance and turbulence. Following can be established in the current review:

1. Increase in oxygen concentration in the intake of IC engine results in increase in exhaust gas, nitrogen and carbondioxide emission.

2. Soot emission is reported to have increasing trend with decrease in NO_X emission.
3. Soot emission is comparatively lower for long route exhaust gas recirculations system.
4. NOX emission decreases with increase EGR rate.
5. Soot formation increases with increase in EGR rate.
6. Flame temperature is reduced due to EGR technology.
7. Power produced by IC is reduced by the use of EGR technology.
8. Use of intercooler and EGR cooler reported to increase the effectiveness of EGR technology.

5. References

[1] K. Shen, F. Li, Z. Zhang, Y. Sun, C. Yin, Effects of LP and HP cooled EGR on performance and emissions in turbocharged GDI engine, Appl. Therm. Eng. 125 (2017) 746–755. doi:10.1016/j.applthermaleng.2017.07.064.

[2] A. Schwarte, F. Kimmich, R. Isermann, Model-based fault detection of a diesel engine with turbo charger - a case study, IFAC Proc. Vol. 36 (2003) 293–306. doi:10.1016/S1474-6670(17)36508-4.

[3] H. Wei, T. Zhu, G. Shu, L. Tan, Y. Wang, Gasoline engine exhaust gas recirculation - A review, Appl. Energy. 99 (2012) 534–544. doi:10.1016/j.apenergy.2012.05.011.

[4] Q. Hu, X. Li, A. Lin, W. Qi, X. Li, X.J. Yang, Total emission control policy in China, Environ. Dev. (2017) 0–1. doi:10.1016/j.envdev.2017.11.002.

[5] L. Shi, Y. Cui, K. Deng, H. Peng, Y. Chen, Study of low emission homogeneous charge compression ignition (HCCI) engine using combined internal and external exhaust gas recirculation (EGR), Energy. 31 (2006) 2329–2340. doi:10.1016/j.energy.2005.12.005.

[6] S. Gan, H.K. Ng, K.M. Pang, Homogeneous Charge Compression Ignition (HCCI) combustion: Implementation and effects on pollutants in direct injection diesel engines, Appl. Energy. 88 (2011) 559–567. doi:10.1016/j.apenergy.2010.09.005.

[7] J.E. Dec, Advanced compression-ignition engines - Understanding the in-cylinder processes, Proc. Combust. Inst. 32 II (2009) 2727–2742. doi:10.1016/j.proci.2008.08.008.

[8] U. Asad, M. Zheng, Exhaust gas recirculation for advanced diesel combustion cycles, Appl. Energy. 123 (2014) 242–252. doi:10.1016/j.apenergy.2014.02.073.

[9] J. Thangaraja, C. Kannan, Effect of exhaust gas recirculation on advanced diesel combustion and alternate fuels - A review, Appl. Energy. 180 (2016) 169–184. doi:10.1016/j.apenergy.2016.07.096.

[10] P. Divekar, Q. Tan, X. Chen, M. Zheng, Characterization of Exhaust Gas Recirculation for diesel low temperature combustion, IFAC-PapersOnLine. 28 (2015) 45–51. doi:10.1016/j.ifacol.2015.10.007.

[11] J.C. Frost, G. Smedler, Control of NOx emissions in diesel powered light vehicles, Catal. Today. 26 (1995) 207–214. doi:10.1016/0920-5861(95)00140-B.

[12] D. Agarwal, S.K. Singh, A.K. Agarwal, Effect of Exhaust Gas Recirculation (EGR) on performance, emissions, deposits and durability of a constant speed compression ignition engine, Appl. Energy. 88 (2011) 2900–2907. doi:10.1016/j.apenergy.2011.01.066.

[13] F. Millo, P.F. Giacominetto, M.G. Bernardi, Analysis of different exhaust gas recirculation architectures for passenger car Diesel engines, Appl. Energy. 98 (2012) 79–91. doi:10.1016/j.apenergy.2012.02.081.

[14] H. Peng, Y. Cui, L. Shi, K. Deng, Effects of exhaust gas recirculation (EGR) on combustion and emissions during cold start of direct injection (DI) diesel engine, Energy. 33 (2008) 471–479. doi:10.1016/j.energy.2007.10.014.

[15] J.M. Hansen, M. Blanke, H.H. Niemann, M. Vejlgaard-Laursen, Exhaust gas recirculation control for large diesel engines - Achievable performance with SISO design, IFAC, 2013. doi:10.3182/20130918-4-JP-3022.00011.

[16] K. Min, D. Jung, M. Sunwoo, Air system modeling of light-duty diesel engines with dual-loop EGR and VGT systems, IFAC-PapersOnLine. 28 (2015) 38–44. doi:10.1016/j.ifacol.2015.10.006.

[17] S. Jafarmadar, P. Nemati, Analysis of Exhaust Gas Recirculation (EGR) effects on exergy terms in an engine operating with diesel oil and hydrogen, Energy. 126 (2017) 746–755. doi:10.1016/j.energy.2017.03.030.

[18] Z. Chen, Z. Wu, J. Liu, C. Lee, Combustion and emissions characteristics of high n-butanol/diesel ratio blend in a heavy-duty diesel engine and EGR impact, Energy Convers. Manag. 78 (2014) 787–795. doi:10.1016/j.enconman.2013.11.037.

[19] E. Galloni, G. Fontana, R. Palmaccio, Effects of exhaust gas recycle in a downsized gasoline engine, Appl. Energy. 105 (2013) 99–107. doi:10.1016/j.apenergy.2012.12.046.

[20] B.H. Engler, J. Leyrer, E.S. Lox, K. Ostgathe, Catalytic reduction of Nitrogen oxide in diesel exhaust gas, 96 (1995) 529–547.

[21] T. Morimune, H. Yamaguchi, Y. Yasukawa, Study of catalytic reduction of NO(x) in exhaust gas from a diesel engine, Exp. Therm. Fluid Sci. 18 (1998) 220–230. doi:10.1016/S0894-1777(98)10025-0.

[22] M. Zheng, G.T. Reader, J.G. Hawley, Diesel engine exhaust gas recirculation - A review on advanced and novel concepts, Energy Convers. Manag. 45 (2004) 883–900. doi:10.1016/S0196-8904(03)00194-8.

[23] O. Angrill, H. Geitlinger, T. Streibel, R. Suntz, H. Bockhorn, Influence of exhaust gas recirculation on soot formation in diffusion flames, Proc. Comb. Inst. 28 (2000) 2643–2649. doi:10.1016/S0082-0784(00)80683-9.

[24] J. Rückert, A. Schloßer, H. Rake, B. Kinoo, M. Krüger, S. Pischingert, Model Based Boost Pressure and Exhaust Gas Recirculation Rate Control for a Diesel Engine With Variable Turbine Geometry, IFAC Proc. Vol. 34 (2001) 277–282. doi:10.1016/S1474-6670(17)34410-5.

[25] G.H. Abd-Alla, Using exhaust gas recirculation in internal combustion engines: a review, Energy Convers. Manag. 43 (2002) 1027–1042. doi:10.1016/S0196-8904(01)00091-7.

[26] H.M. Kim, D.H. Lee, S.K. Park, K.S. Choi, H.M. Wang, An experimental study on heat exchange effectiveness in the diesel engine EGR coolers, J. Mech. Sci. Technol. 22 (2008) 361–366. doi:10.1007/s12206-007-1102-x.

[27] R. Moos, B. Reetmeyer, A. Hürland, C. Plog, Sensor for directly determining the exhaust gas recirculation rate-EGR sensor, Sensors Actuators, B Chem. 119 (2006) 57–63. doi:10.1016/j.snb.2005.11.055.

[28] F. Millo, P.F. Giacominetto, M.G. Bernardi, Analysis of different exhaust gas recirculation architectures for passenger car Diesel engines, Appl. Energy. 98 (2012) 79–91. doi:10.1016/j.apenergy.2012.02.081.

[29] S. Mohankumar, P. Senthilkumar, Particulate matter formation and its control methodologies for diesel engine: A comprehensive review, Renew. Sustain. Energy Rev. 80 (2017) 1227–1238. doi:10.1016/j.rser.2017.05.133.

[30] M.R. Malayeri, T. Zornek, S. Balestrino, A. Warey, P.G. Szymkowicz, Deposition of nanosized soot particles in various EGR coolers under thermophoretic and isothermal conditions, Heat Transf. Eng. 34 (2013) 665–673. doi:10.1080/01457632.2012.738320.

[31] A. Al-Janabi, M.R. Malayeri, Turbulence induced structures in Exhaust Gas Recirculation coolers to enhance thermal performance, Int. J. Therm. Sci. 112 (2017) 118–128. doi:10.1016/j.ijthermalsci.2016.10.005.

[32] B. Rajesh Kumar, S. Saravanan, D. Rana, V. Anish, A. Nagendran, Effect of a sustainable biofuel - N-octanol - on the combustion, performance and emissions of a di diesel engine under naturally aspirated and exhaust gas recirculation (EGR) modes, Energy Convers. Manag. 118 (2016) 275–286. doi:10.1016/j.enconman.2016.04.001.

[33] A. Maiboom, X. Tauzia, J.F. Hétet, Experimental study of various effects of exhaust gas recirculation (EGR) on combustion and emissions of an automotive direct injection diesel engine, Energy. 33 (2008) 22–34. doi:10.1016/j.energy.2007.08.010.

Appendix

Comp.	compressor
Cat.	Catalytic converter
C	compressor
DPF	Diesel Particulate Filter
DPT	Diesel Particulate Trap
EGR	Exhaust Gas Recirculation
HP	High Pressure
HCCI	Homogeneous Charge Compression Ignition
IC	Internal Combustion
LR	Long Route
LP	Low Pressure
LTC	Low Temperature Combustion
NOx	Oxides of Nitrogen (NO and NO2 etc.)
PID	Proportional Integral Derivative
PCCI	Premixed Charge Compression Ignition
SR	Short Route
SOx	Oxides of Sulphur
Turb.	turbine
USEPA	United Sates Environmental Protection Agency