Journal of Physics: Conference Series

PAPER • OPEN ACCESS

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To cite this article: R Murali *et al* 2021 *J. Phys.: Conf. Ser.* **2051** 012044

A review on the correlation between exhaust backpressure and the performance of IC engine

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Abstract. The exhaust system in any Internal Combustion (IC) engine is a critical component that affects the engine's performance. A poorly designed exhaust system generally results in an increment of exhaust backpressure. Backpressure is one of the fluid's characteristics that acts as a resistance to exhaust gas flow. Relatively higher backpressure blocks the exhaust gas flow from discharging efficiently, decreasing the engine's performance. In general, higher backpressure results in power and torque loss as well as higher fuel consumption and emission to the environment. This review paper aims to elucidate the relationship between exhaust backpressure and the performance of IC engine. Various past studies were conducted to study the effect of exhaust backpressure on the performance of IC engine through Computational Fluid Dynamic (CFD) simulation, engine simulation and experimental analysis. Some studies used Taguchi's method to optimize the exhaust manifold's design in respect to backpressure decrement. It was found that 0.22 kW to 0.45 kW of engine's power increases for every 1 kPa of exhaust backpressure decrement. At the same time, 1.5% to 3% of fuel consumption decreases for every 10 kPa of backpressure decrement. In contrast, higher backpressure does reduce the Nitrous Oxides (NOx) emission in the exhaust gas due to higher temperature. Therefore, exhaust backpressure must be minimized to improve any IC engine's performance if the NOx emission is neglected. This review paper is expected to provide a better understanding of the impact of exhaust backpressure on IC engine's performance.

1. Introduction

Internal Combustion (IC) engine could be mainly classified into two categories which are the Spark Ignition (SI) engine and Compression Ignition (CI) engine [1]. The main difference between both types of IC engine will be the combustion process. In the SI engine, combustion will occur through a spark produced by a spark plug, while in the CI engine, combustion will occur through a higher compression ratio which will rise the in-cylinder temperature above the fuel ignition temperature and causes the fuel to self-ignite [2]. Nevertheless, both IC engine types have a similar purpose which is to convert the chemical energy from fuel to mechanical energy through combustion [3]. Two main components play a crucial role in maximizing the IC engine's performance, which will be the intake system and the exhaust system, [1]. Even though the intake system dominates the cylinder filling process, the exhaust system is equally essential to discharge the combustion product efficiently. The exhaust system's design is a critical factor that will influence the IC engine's overall performance. A poorly designed exhaust system will generally result in backpressure increment [4], [5], [6].

Backpressure is one of the fluid's characteristics that acts as a resistance to the exhaust gas flow in the exhaust system [7], [8]. Relatively high backpressure will block the flow of exhaust gas and will cause negative consequences to the IC engine's performance. Generally, it is accepted that higher backpressure will reduce the performance of SI and CI engine, such as power [9], torque, [10] and fuel consumption [11]. Moreover, backpressure is also a critical factor that creates harmful emissions to the environment through exhaust gas discharge [7], [12]. However, backpressure could not be eliminated due to transmission loss and insertion loss in the muffler [13]. The muffler in an exhaust system plays a vital role to dampen the sound energy emitted to the environment. This could only be achieved through the existence of transmission and insertion loss, as backpressure will increase these losses. Hence, backpressure needs to be in optimal range so that maximum engine's performance could be achieved, and at the same time, sound energy could be dampened up to the legal limit. The aim of this paper was to correlate the relationship between exhaust backpressure to the performance of IC engine by reviewing various past research. Thus, elucidation that is found through vast study in this paper could be used to provide a better understanding of the impact of backpressure to IC engine.

2. Impact of Exhaust Backpressure to the Torque and Power of an IC Engine

Generally, backpressure gives negative consequences to the performance of an IC engine. Since backpressure acts as a resistance to the exhaust gas flow, the piston in either SI or CI engine has to do extra pumping work to evacuate the exhaust gas out of the cylinder. This causes the engine to lose a particular portion of its power and torque. Researches have conducted various studies to correlate the relationship between exhaust backpressure to the engine's power and torque of SI and CI engine. In 2003, Hwang, Lee & Kim conducted an experiment to optimize an exhaust muffler's design to improve the engine's performance. It was documented that 90% of the engine's lost torque is recovered when the backpressure is reduced in the new optimized exhaust muffler, [14]. Similarly, in 2006, Lahousse et al. studied the impact of exhaust catalyst backpressure in the SI engine, and it was found that the torque increased by 5.5Nm when 40% of the catalyst backpressure is reduced [10].

Like torque, backpressure causes the engine to lose some power as it has to do more pumping work to discharge the exhaust gas out of the cylinder. This happens because the piston's movement needs to oppose the exhaust backpressure, which acts as a resistance to exhaust gas flow. In 2009, Pesansky et al. investigated the impact of three-way catalyst selection on the backpressure and the engine's performance. The study concluded that the engine's power decreased by 4 kW when the backpressure increased by 7.3 kPa (1.06 psi) in the 5.4L SI engine. The study had also concluded that for every 1 kPa of backpressure, the 5.4L SI engine would lose 0.44 kW of power [9]. In general, it was also documented that an IC engine loses 0.3 kW of power for every 1 kPa of exhaust backpressure, [9], [15]. Similarly, in the year 2016, Srinivas, Mamila, Rao & Ahmed mentioned that when 3.3 kPa backpressure increases, 0.74 kW to 1.5 kW of the IC engine's power will be lost. It was also mentioned that 3.3 kPa backpressure would decrease 1% of the engine's power [16]. Therefore, it could be concluded that 0.22 kW to 0.45 kW of engine's power will be lost for every 1 kPa of exhaust backpressure in the IC engine.

3. Impact of Exhaust Backpressure to the Fuel Consumption and Emission of IC Engine

Higher backpressure will also contribute to higher fuel consumption of any SI or CI engines regarding power and torque decrement. Extra fuel must be burnt to overcome the exhaust system's resistance, mainly due to exhaust backpressure. In the early 1970s, fuel consumption was documented to increase by 3% for every 10 kPa of exhaust backpressure in naturally aspirated engines. While in a turbocharged engine, for every 10 kPa of exhaust backpressure increment, 1.5% of fuel consumption increase was documented [11]. In the year 1981, Kleinhenz & Schmeichel studied the impact of exhaust backpressure on the fuel consumption in CI engine, and it was found that on average, 1.5% of brake specific fuel consumption (bsfc) does increase for every 5.5 kPa to 10 kPa of exhaust backpressure in a rpm range of 1800 to 1950 [17]. Similarly, in the year 2010, Roy, Joardder & Uddin investigated the correlation of exhaust backpressure to the performance of CI engine and documented that increase in bsfc was significant at higher rpm range in between 950 to 1200 while in 650 rpm (lower rpm), the backpressure shows less effect on the bsfc [18]. In the year 2009, Pesansky et al. stated in their research that the fuel consumption did increase by 0.005 kg/kW*hr for 14 kPa of backpressure increase in 5.4L SI engine [9]. In 2006, Bugarski, Schnakenberg & Patts experimented the impact of diesel particulate filter on CI engine performance and found that the fuel consumption increased from 1.5% to 2.5% for every 10 kPa of exhaust backpressure [12]. In the year 2004, Sutton et al. investigated the implementation of lubricant blocking of diesel particulate filters in CI engine and found that the fuel consumption did increase by 1.59% at 1500 rpm for 85.4% of backpressure increment while 0.72% of increase at 1700 rpm for 87.8% of backpressure increment [19]. Hence, it could be concluded that the general turbocharged IC engine's fuel consumption will increases by 1.5% for every 10 kPa of backpressure. When it comes to a standard CI engine, 1.5% to 3% of fuel consumption will increase for every 10 kPa of backpressure. For a standard SI engine, 1.5% of fuel consumption will increase for every 10 kPa of backpressure.

In general, the existence of exhaust backpressure will increase the harmful emissions that is introduced to the environment through exhaust gas such as carbon monoxide (CO), carbon dioxide (CO2), nitrous oxides (NOx), hydrocarbon (HC) and particulate matter (PM). NOx formation is always very active in lower temperature and usually slightly higher in Diesel engine [20]. Therefore, most motorized vehicle manufacturers will implement exhaust gas recirculation (EGR) in the CI engine's exhaust system to increase the exhaust gas temperature, which will then decrease the NOx content. In 1999, Baert, Beckman & Veen mentioned in their study that the implementation of exhaust gas recirculation (EGR) increases the backpressure, which then causes PM emission to increase for 12L turbocharged CI engine, but the fuel consumption was documented to show a decreasing trend [21]. Similarly, in the year 2009, Peixoto et al. stated that increasing the EGR's rate reduces the NOx formation and fuel consumption. They have also mentioned that EGR does cause exhaust backpressure increment, which increases the combustion delay and HC emission [22]. In contrast to that, in the year 2007, Millo et al. documented that EGR implementation managed to decrease the NOx by 13% but still cause the fuel consumption to increase due to higher exhaust backpressure [23]. Thus, it could be said that the implementation of EGR could decrease the NOx formation of IC engine, but it will still increase the PM and HC emission and the combustion delay. The fuel consumption will decrease if the EGR rate dominates the exhaust backpressure and vice versa.

In most of the IC engine, a certain percentage of the exhaust will be still trapped inside the combustion chamber, known as a residual gas fraction (RGF) due to backpressure existence [24]. This will indirectly increase the exhaust gas temperature and reduce the NOx formation usually limited to 2-3% [16]. In 2011, Cong, Garner & Cowan investigated the impact of backpressure on conventional and low-temperature diesel combustion and mentioned that RGF increases by 4% for every 1 bar of exhaust backpressure [24]. When RGF increases, the charge temperature will increase, which will affect the combustion efficiency and decrease the NOx formation. In the year 2008, Mayer has mentioned that increasing backpressure in CI engine decreases combustion efficiency [25]. In 2006, Bugarski et al. mentioned in their paper that the soot did increase by 89% for every 10 kPa of exhaust backpressure [12]. In 2009, Pesansky et al. stated that 0.05% of CO increased for 14 kPa of backpressure increase, [9]. In contrast, in the year 2010, Roy et al. experimented the impact of backpressure on the performance of the CI engine. It was found that the CO increment was significant at lower rpm in between 650 to 950, but it did decrease at 1200 rpm (higher rpm) [18]. Thus, it could be concluded that the backpressure existence will increase all type of emissions except for NOx in either SI or CI engine.

4. Critical Review

Table 1 shows the critical review on the impact of backpressure on the IC engine. It summarizes the negative influences such as power and torque decrement and fuel consumption and emission increment.

Table 1. Critical Review on impact of backpressure to IC engine

Study	Type of engine		Remark
	SI	CI	
(Lahousse et al., 2006)	✓		• 5.5 Nm torque increase when 40% catalyst backpressure (BP) decreased, [10]
(Pesansky et al., 2009)	✓		• Fuel consumptions increase by 0.005kg/kw*hr per 14 kPa BP • CO2 emission increase by 0.05 % per 14 kPa BP, [9]
(Roy et al., 2010)		✓	• Bsfc increases when BP increases at 950 and 1200 rpm but shows no impact at 650 rpm • CO increases when BP increases at 650 rpm but decreases at 950 and 1200 rpm, [18]
(Leman et al., 2016)	✓	✓	• The catalytic converter in an exhaust system will increase BP but decreases CO, unburned HC and NOx, [26]
(Pannone & Mueller, 2001)	✓	✓	• IC engine will lose 0.3kW power for 1 kPa BP, [15]
Cong et al., 2011)		✓	• 1 bar BP will increase RGF by 4% which will decrease oxygen content, affect the combustion efficiency, [24]
(Mayer, 2008)		✓	• Higher BP increases bsfc and combustion efficiency, [25]
(Millo et al., 2007)		✓	• EGR fitting increases BP which increases PM but decreases fuel consumption, [23]
(Peixoto et al., 2009)		✓	• Increasing EGR rate decreases bsfc and NOx but increases HC, [22]
(Bugarski et al., 2006)		✓	• Bsfc increases from 1.5%-2.5% for 10 kPa BP • Soot increases by 89% for 10 kPa BP, [12]
(Sutton et al., 2004)		✓	• At 1500 rpm, fuel consumption increases by 1.59% for 84.4% BP increase • At 1700 rpm, fuel consumption increases by 0.72% for 87.8% BP increase, [19]
(Kleinhenz & Schmeichel, 1981)		✓	• Average 1.5% increase in bsfc is documented on varying backpressure which is 5.5 kPa to 10 kPa on 1800 rpm and 1950 rpm respectively, [17]
(Srinivas et al., 2016)		✓	• Every inch of Hg backpressure increase will approximately decrease 1-2 horsepower • Increase in backpressure will increase fuel consumption, PM and CO, [16]
(Hwang et al., 2003)	✓		• Standard muffler cause the engine to lose 10% power due to higher BP, [14]
(Baert et al., 1999)		✓	• EGR fitting increases BP that increases PM emission and fuel consumption, [21]

5. Conclusion

In conclusion, exhaust backpressure causes negative consequences to either SI or CI engine's performance. However, exhaust backpressure could not be eliminated due to the existence of transmission loss and insertion loss in the muffler which are essential to dampen the sound energy to the environment. Moreiver, backpressure increses all harmful emissions through exhaust gas except for NOx. Hence, backpressure must be optimal by optimizing the design of the exhaust system, especially the exhaust manifold and the silencer, to maximize the performance of the IC engine, reduce the overall emission through exhaust gas and maintain the sound energy emitted to the environment up to the legal limit. From the extensive review in this paper, the impact of the exhaust backpressure to the performance of the IC engine could be concluded as:

- Higher exhaust backpressure reduces the torque of the engine. Roughly 5.5 Nm of torque could be recovered by reducing 40% of backpressure.
- Higher exhaust backpressure reduces the power of the engine. For every 1 kPa of backpressure, 0.22 kW to 0.45 kW of engine's power is lost.
- Higher backpressure increases the fuel consumption of the IC engine. For every 10 kPa of backpressure, fuel consumption increases by 1.5% to 3%.
- Increase in backpressure causes RGF increment and combustion efficiency decrement.
- Harmful emissions such as CO, HC and PM increases due to higher backpressure.
- Soot emission increases when backpressure increases. For every 10 kPa of backpressure, 89% of soot increases.
- However, NOx emission decreases due to higher backpressure limited to 2-3%.

6. Acknowledgments

The author would like to acknowledge the support from the Fundamental Research Grant Scheme (FRGS) under a grant number of FRGS/1/2020/TK0/UNIMAP/02/97 from the Ministry of Higher Education Malaysia. Furthermore, the authors acknowledge the staff at the Center of Excellence Automotive and Motorsport and Faculty of Mechanical Engineering Technology, Universiti Malaysia Perlis (Malaysia) and Modenas Sdn.Bhd (Malaysia) Research and Development Department for their productive discussions and input to the research. Contributions from everyone directly or indirectly to this study are highly appreciated.

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