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Effect of a new wet soot absorber on soot removal of a diesel engine

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Abstract. In the following investigation, a submerged-type Wet Soot Absorber (WSA) is studied, and its capability to reduce the soot emission level of a four cylinder, Direct Injection (DI) diesel engine is evaluated. The WSA can provide a large contact area between water and exhaust flow, which increases the soot capturing probability. Hence, the system can be more compact and suitable for vehicle engine applications. The ECE-R49 standard test is followed to assess the effect of the WSA on engine performance and soot emission. The experiments revealed that a soot removal efficiency of 70% is attained under full-load engine operating conditions, due to the high momentum of exhaust gas flow entering the chamber of the unit and providing more flow penetration into the water. Also, further bubble break-up in high gas velocity results in a larger liquid-gas interface and contributes to better soot removal. The minor negative effects of utilizing the WSA on Brake Specific Fuel Consumption (BSFC) are also compared with those of conventional DPFs, and the advantages of WSA are discussed.

1. Introduction

During the last decade, diesel engines have attracted extensive attention in transportation industries and redirected the preference of automotive manufacturers, due to their high thermal efficiency and rather low fuel costs [1]. However, there are some concerns regarding the emissions of Compression Ignition (CI) engines, restricting their worldwide application. Diesel engines produce significant amounts of nitrogen oxides and soot compared to the conventional spark ignition engines [2,3]. Nitrogen oxides, known as NO_x, have long been considered a serious threat to human health, and the hazard to the human body of emitted soot from diesel engines has been recently evaluated systematically. Soot effects on climate change and the environment are also addressed in the literature [4,5]. Actually, engine combustion improvement and modification of fuel structures have a great significance in the suppression of soot and Particulate Matter (PM) (4) [6-11]. According to available studies, in-cylinder parameters, such as fuel injection pressure, injection timing, spray geometry, air/fuel swirl ratio, turbo-charging, combustion chamber shape, wall temperatures and Exhaust Gas Recirculation (EGR), seem to play a critical role in terms of controlling diesel combustion emissions. Another approach which contributes to the emission restriction of diesel engines is utilizing alternative fuels. Fuel additives and bio fuels provide a rather promising resolution for emission suppression in diesel engines [12-

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17]. However, the strict emission regulations applied to diesel engines urge the necessity of utilizing after-treatment devices to capture soot and PM contained in engine exhaust. Diesel Particulate Filters (DPFs) and Selective Catalytic Reduction (SCRs) have been recently developed to maintain the level of emitted soot under a reasonable level in the CI engine [18-20], while the removal efficiency of these after-treatment devices has been proven up to 99% [21]. Depending on filter type and age, engine size, sampling methods, and fed fuel [22,23], using DPFs and SCRs imposes extensive problems including their regeneration and renewal requirements. For instance, in one of the most recent surveys, Dilip et al. [24] studied heating techniques for the regeneration of a stainless-steel mesh-type particulate filter. Their theoretical estimation shows that the induction heating approach for regeneration via exhaust gas heating requires high power (> 3 kW). Moreover, one of the serious challenges that DPFs face is the inevitable pressure drop in the exhaust route, which leads to an increase in the engine pumping work and causes additional specific fuel consumption [25,26]. Similarly, common defects with SCRs appear to be their limited temperature operation circumstances, the small residence time of the exhaust gas, catalyst poisoning, ammonia leakage and the discharge of catalyst mass under high temperature conditions, which circumscribe their application [27-29]. Due to the drawbacks associated with utilization of the above techniques, some new approaches are employed to trap diesel particulate matter. A traditional group of these methods are based upon particle inertia and is known as cyclonic particulate filtration. Arcoumanis et al. [30] developed a cyclone-based particulate trap for an EGR-equipped, high-speed diesel engine. With the help of enhanced particulate agglomeration provided by a cooling heat exchanger system, the authors reported a removal efficiency of up to 77%. Another method uses electrostatic forces to capture the particulates that are highly electrically charged. Several researchers have worked on the electrostatic agglomeration of aerosols produced by diesel engines for automotive applications [31,32]. Saiyasitpanich et al. [33] enhanced the PM removal ability of the conventional electrostatic agglomerators by combining the electrostatic effect with the effect of a wet surface in capturing diesel particulate matter. The design benefits from the adhesion occurring in the solid-liquid interface, which happens on the wet wall surface of a tubular chamber, to trap soot particles. The above precipitator was evaluated on a non-road electricity generator diesel engine. There are various advantages of this method, including low maintenance costs, slight backpressure, plain operation and the ability to collect recycled soot. Also, Carotenuto et al. [34] developed a mathematical model to assess the particle removal efficiency in wet electrostatic scrubbers. The use of exhaust gas washing to reduce diesel exhaust emissions of a stationary diesel engine was lately pursued by Roy et al. [35]. They benefited from the ability of water to absorb exhaust soluble gas components, such as white smoke, NO_x, CO and CO_2, to reduce the exhaust odor. Also, a significant reduction of 85% in black smoke emission is observed in their work. In spite of the rather high smoke reduction efficiency, the large size of their apparatus makes it difficult to be implemented on vehicle diesel engines. Roy et al. employed a 2.75 m-long washing tower in order to purify the exhaust smoke of a single-cylinder, 4.47 kW, stationary diesel engine.

In the present study, a new design for a wet soot absorber has been experimentally investigated on a diesel engine. In the proposed WSA, the downward gas flow from the exhaust pipe submerged into the water provides an extended gas-liquid interface that can improve the removal of diesel particulate matter. This design can provide the chance for WSAs to be mounted on non-stationary diesel engines in automotive industries due to its compactness and mobility. Effects of the wet soot absorber on removal efficiency and Brake Specific Fuel Consumption (BSFC) in a typical DI-diesel engine were also evaluated and the results compared with those of a recent study concerning common soot removal technologies.

2. Test setup

2.1. Diesel engine test bench

The schematic drawing of the test bed in Figure 1 shows the OM314- DI diesel engine, the specifications of which are presented in Table 1. The engine is coupled to a hydraulic DDX Heenan & Froude dynamometer to vary the engine load. A commercial diesel fuel was used in all the tests. To measure the intake air flow, an orifice-fitted surge tank is employed. Also, a computer

Table 1. Test engine specifications.

Engine type	Compression ignition (naturally aspirated)
Number of cylinders	4
Combustion chamber	Direct injection
Piston shape	Bowl-in shaped
Bore × stroke (mm)	97 × 128
Piston displacement (cc)	3784
Compression ratio	17:1
Maximum power (h.p)	85
Maximum torque (N.m)	235
Maximum speed (rpm)	2800
Mean effective pressure (bar)	6.8@2800 rpm
Injection pressure (bar)	240

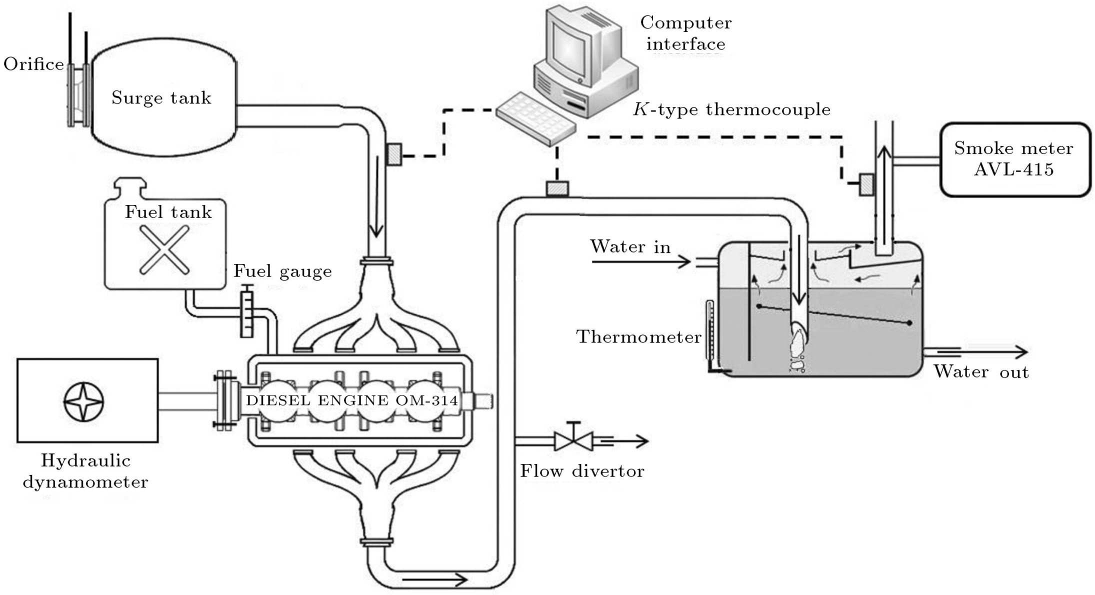

Figure 1. Test bed components.

Table 2. Accuracy of measurement devices.

Device	Error (%)	Unit
Pressure gauge	1	mmHg
Thermocouple	0.01	°C
Dynamometer	1	N.m
Speed meter	0.1	rpm
Flow meter	1	Lit/min
Smoke meter	0.01	gr/cm^3

interface unit is provided to measure the temperature of inlet air at the orifice and the exhaust gases entering and exiting the WSA, utilizing K-type thermocouples. Soot particulate mass concentration was recorded for every test step with an AVL-415 smoke meter, which could also measure the exhaust opacity by Flow Soot Number (FSN). In its system, after the filter paper is exposed to the exhaust flow sample, the bulb illuminates the filter paper via a light guide. The reflected light, which depends on paper blackness, is registered by means of a photodiode. At the beginning of each test series, the smoke meter was calibrated taking the smoke content of the surrounding environment as the reference. The accuracy of measurement devices is available in Table 2.

2.2. WSA characteristics and modifications

The investigated WSA comprises a rectangular chamber, 60, 30 and 60 centimeters in length, width and height, respectively, constructed using a galvanized metal sheet, to which the 2 in exhaust pipe with raw exhaust is introduced and from which the treated exhaust leaves. The chamber is filled with water to 30 centimeters and supported by a couple of baffles to prevent water from over splashing or high waviness. The baffles arrangement was developed during the project and required several trial-and-error experiments to assure the baffles reliability in preventing water from producing unrestrained waves. All connections and edges were sealed with a silicon paste that could tolerate temperatures exceeding 350°C. The soot removal process is based on the interaction occurring between the exhaust flow and water, through which the soot particles contained in the exhaust flow stick to the water surface. Various mechanisms are engaged in the process of separating soot particles from the exhaust gases in the wet absorber. Tremendous splashing caused by exhaust flow can enhance the mixing of the exhaust flow and water, which improves the gas-liquid encounter. Also, the gas void fraction, which is dependent on the average gas velocity, plays a critical role in terms of changing the gas-liquid interface area. Moreover, the cooling and expanding of the exhaust flow along the wet passage through the absorber can increase the chance of soot deposition, due to the increase in flow density and the resulting reduction of flow velocity. Several configurations, i.e. the adjustment of the entering pipe position, with respect to the water surface and location of the baffles, have been tested to come up with an optimum design that could guarantee the best soot removal efficiency and simultaneously retain the stillness of water inside the chamber. Figure 2 represents four different arrangements of introducing the exhaust gas flow of the diesel engine to the WSA. In the first case (Case A), the absence of baffles allowed a significant water leakage from the exit pipe, which caused smoke meter failure. In Case B, because of inappropriate mixing and lack of splashing, the removal of soot and

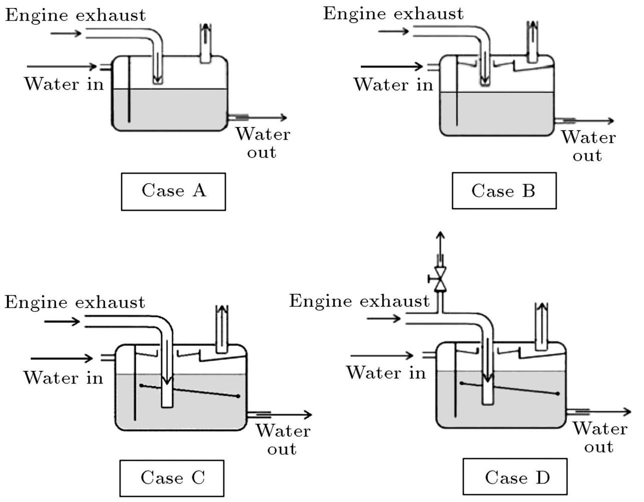

Figure 2. Modifications of the WSA.

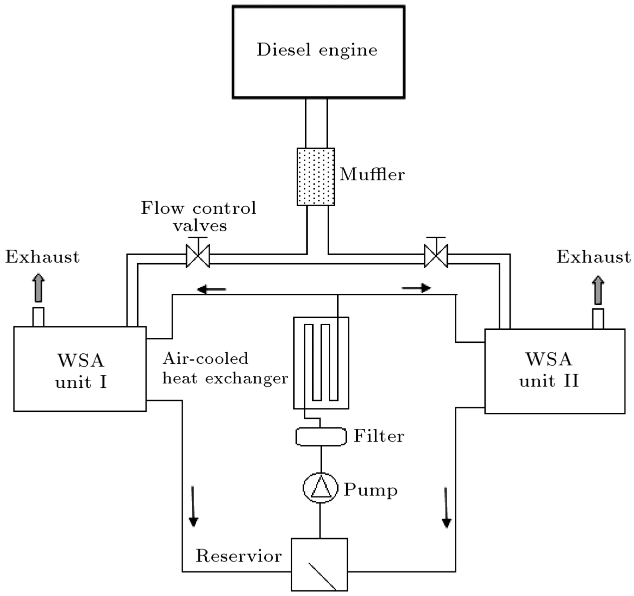

Figure 3. Double-unit WSA for implementation on real applications.

particulates, especially at low engine speeds, does not happen as desired. By drowning the exhaust-delivery tube into the water (Case C), the removal efficiency might increase to a considerable level, but some severe problems are associated with this strategy, such as extreme water evaporation and dangerous vibrations of the chamber. To avoid such problems, only a fraction of the exhaust flow of the test engine should be introduced to WSA by means of a flow diverter (Case D). The flow diverter used for this purpose was adjusted continuously to guide only 75 percent of exhaust flow to the WSA.

The arrangement of Case D was developed and used by fitting the water level at 30 cm and the exhaust pipe position at $H/D = 2$, where H and D stand for the height of the pipe beneath the water level and the pipe inner diameter, respectively. In order to compensate for the evaporating water and to keep the water temperature under a reasonable limit (20-40°C), in this prototype design, water was fed into the chamber at the rate of 300 lit/hr.

Actually, the open water circulation was employed in the experimental procedure for the purpose of isolating the water temperature from other variables, i.e. mass flow rate of exhaust, exhaust temperature, etc. A close water circulation system with a water inter-cooler would be acceptable to be mounted on a commercial diesel engine. The wet soot absorber with multiple units can fulfill the PM emission removal of various light-to-heavy-duty diesel engines. Depending on the particular applications, one or several identical WSA units can be joined together in different arrangements. For clarification of this idea, a double-unit configuration suggested for real practice is depicted in Figure 3. The appropriate design for real applications requires specific considerations for additional components such as a water cleaning filter and a water inter-cooler. However, it would be expected that the tank water requires renewal at one-day intervals in case of constant use. Based on the particular size and maintenance periods of the WSA, used water can be purified via several available methods that are able to regenerate water at different levels [36-38].

3. Test procedure

For the purpose of evaluating the effect of the WSA implementation on reducing the soot level emitted from the diesel engine, the experiments were conducted according to the ECE-R49 standard test. This standard is a 13-step test in which the engine is studied under several operating conditions. This test cycle assigns a weighting factor to each test step, which implies the predominance of the conditions under which the engine is running. At each step of the test, the engine performance and soot emission were examined with and without the implementation of WSA. Table 3 shows the conditions of the WSA and the OM314 diesel engine at 13 operating points dictated by the ECE-R49 standard.

With the intention of making enough assurance for the repeatability of the tests, each test step was repeated at least twice on different days.

4. Results and discussion

4.1. Effect of the WSA on soot emission

Figure 4 presents the exhaust soot mass flow rate with and without the implementation of WSA. Also, Figure 5 shows the mass removal efficiency of the WSA, using Eq. (1) shown in Box I.

As Figure 4 declares, in the early stages of the test, in which the engine is running at idle or low

Table 3. Working conditions of WSA under different engine loads and speeds.

Test no.	Exhaust temp. before WSA (°C)	Exhaust temp. after WSA (°C)	Exhaust momentum (Ns)	WSA water temperature (°C)	Engine load (N.m)	Engine speed (rpm)	Weighting factor
1	75.14	21.6	0.28	21	~ 0	800	0.066
2	122.13	28.8	0.84	23	18	1800	0.08
3	148.16	32.9	0.91	25	45	1800	0.08
4	197.91	38.7	1.04	27	90	1800	0.08
5	253.8	42.6	1.18	29	135	1800	0.08
6	338.9	46.7	1.40	35	180	1800	0.08
7	108.3	33	0.33	38	~ 0	800	0.066
8	451.8	50.8	3.07	40	160	2800	0.08
9	403.4	52.4	2.79	36	120	2800	0.08
10	330.5	51.3	2.42	37	80	2800	0.08
11	258.2	48.3	2.10	41	40	2800	0.08
12	218.5	46.8	1.93	48	16	2800	0.08
13	92.1	31.3	0.26	42	~ 0	800	0.066

$$\eta_{\text{removal}} = 100 \times \frac{\text{Exhaust soot mass flow without WSA} - \text{Exhaust soot mass flow with WSA}}{\text{Exhaust soot mass flow without WSA}}. \quad (1)$$

Box I

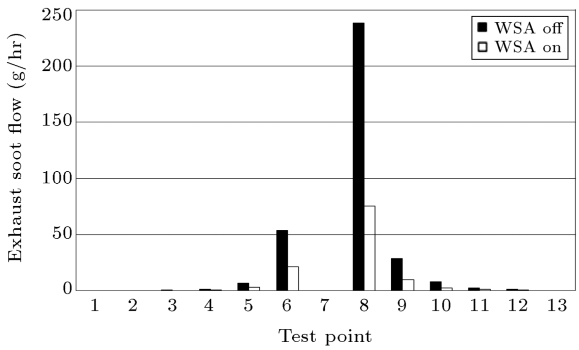

Figure 4. The variations of exhaust soot mass flow with and without WSA.

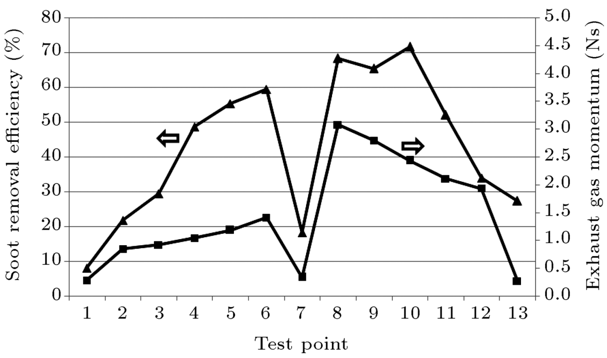

Figure 5. Simultaneous presentation of soot removal efficiency (▲) and entering exhaust momentum (■).

loads of 1800 rpm and the lean combustion regime is prevailing (points 1, 2 and 3), the soot content of the exhaust is inconsiderable. Also, Figure 5 shows that the effect of the WSA in reducing the soot content of the exhaust gases is not satisfying at the early points. This might be due to the insufficient momentum of the exhaust gases, which cannot provide enough exhaust gas penetration into the water for soot removal. The same fact also rules for idle conditions of points 7 and 13. The gas momentum at each operating point is calculated as the multiplying of exhaust mass flow by exhaust flow velocity. The mass flow rate is a summation of intake air mass and injected fuel mass. Considering the exhaust gases as an ideal gas mixture, and by having exhaust pressure, temperature, mass flow and gas constant, the exhaust volumetric flow and, hence, the exhaust velocity, can be obtained. According to the ideal gas state equation and measured exhaust temperature, the exhaust flow velocity could be estimated. The exhaust momentum calculation is presented via Eqs. (2) and (3):

$$\text{Exhaust momentum} = (\dot{m}_{\text{fuel}} + \dot{m}_{\text{air}}) \times V_{\text{Exh}}, \quad (2)$$

$$V_{\text{Exh}} = \frac{(\dot{m}_{\text{fuel}} + \dot{m}_{\text{air}}) \times R_{\text{mixture}} \times T_{\text{Exh}}}{P_{\text{Exh}}} \frac{1}{A_{\text{tube}}}. \quad (3)$$

In Eqs. (2) and (3), $\dot{m}_{\text{fuel}}$ and $\dot{m}_{\text{air}}$ represent the fuel and mass flow rate, respectively. Exhaust velocity (V_{Exh}) is also calculated via the equation of state, Eq. (3), where R_{mixture} is equal to air gas constant and T_{Exh} and P_{Exh} are exhaust temperature and pressure, respectively. Finally, A_{tube} is the exhaust tube cross-section area.

For points 4, 5 and 6, at which the momentum of exhaust gases is increasing, the comparison between raw and treated exhaust gases in Figure 4 clearly shows the growing effectiveness of the WSA in trapping soot particles. This lies within the fact that the appropriate mixing, followed by high velocity exhaust gases, can increase the chances of collision between soot particles and water. The same trend is observed in Figure 5 in which the removal efficiency is improved by the increase of exhaust momentum. Since the momentum of gas flow attains a high level at Stage 8, great removal performance is observed at this point. The increase of soot removal, followed by the increase of gas momentum, can also be interpreted as follows: bubble diameter decreases with superficial gas velocity [39,40], which is due to the increased bubble breakup at higher gas flow rates, creating a greater number of smaller bubbles. Hence, by extending the gas-liquid interface, enhanced soot removal can be expected.

The difference between the variations of removal efficiency and exhaust momentum during test points 8 to 10 can possibly be caused by the rising water temperature of the tank, which could make up for the low momentum gas effect in absorbing exhaust PM. Continuing the test stages at 2800 rpm (from point 10 up to 12), it is observed in Figure 5 that by reducing engine load, soot removal gradually declines, due to reduced exhaust momentum.

The results declared that when the engine is running under high load conditions, where smoke is significantly produced, the WSA performs at its best in reducing the soot level. In order to examine the repeatability of the results, the tests were repeated twice on different days, and the removal efficiency in both test series had acceptable agreement.

4.2. Effect of the WSA on BSFC

Figure 6 displays the effect of the implementation of WSA on Brake Specific Fuel Consumption (BSFC) for different testing points. The dominant issue in this figure is the increase of BSFC caused by setting up the WSA, which generally imposes extra backpressure in the exhaust route. Therefore, the engine must provide extra p-V work to overcome the increased exhaust manifold pressure. Thus, the extra work required will result in higher fuel consumption.

At test points 5 and 8, which are located at high load conditions, a slight improvement of BSFC is observed by the implementation of WSA. It can be probably explained via the noticeable effect of exhaust backpressure on cylinder residual mass accumulation under high load operating conditions [41]. The increase of in-cylinder residual mass can provide appropriate conditions for auto-ignition and, hence, shorten the combustion delay by providing high temperature surroundings [42]. Therefore, under such conditions, the contribution of excess backpressure in shortening the combustion delay virtually offsets the negative effects of backpressure on specific fuel consumption.

The superiority of the wet absorbers over conventional DPFs in vehicle diesel engines is highlighted through their minor effect on increasing BSFC. For the sake of clarity, the present experimental results of the effect of WSA on the increase of BSFC are compared with those of a study concerning the effect of using DPFs on the increase of diesel fuel consumption [26]. The comparison is established for low and high engine speeds and is depicted in Figure 7. In Figure 7, the

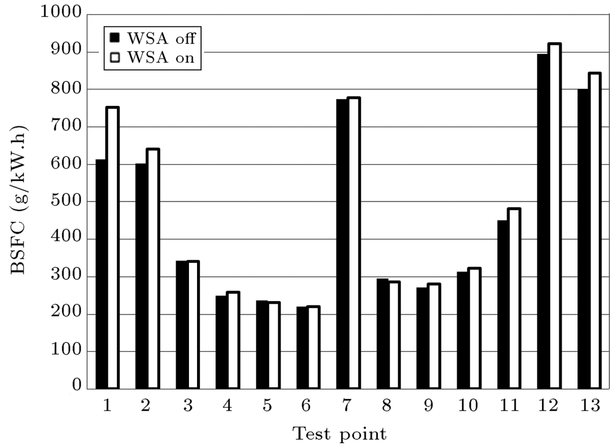

Figure 6. The variations of engine BSFC with and without WSA.

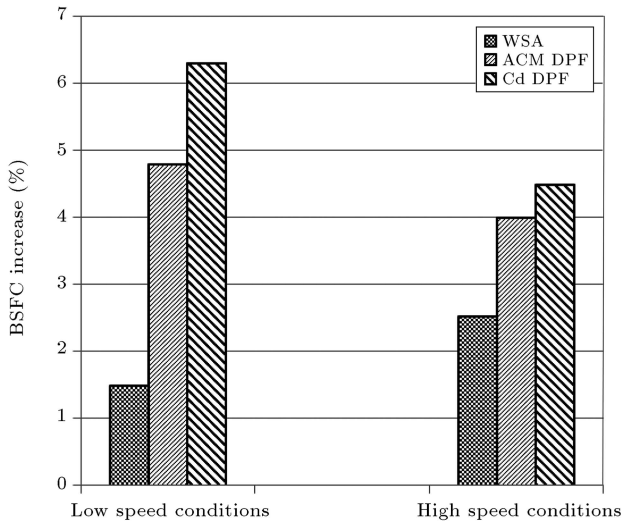

Figure 7. Comparison of BSFC increase affected by installation of soot agglomeration devices.

investigated WSA is compared with two conventional types of DPFs: cordierite DPF (Cd) and Acicular Mullite DPF (ACM) in terms of their impact on the increase of specific fuel consumption. In fact, the column with the checker pattern represents the average percentage of WSA effect (either positive or negative) on engine BSFC for each speed. Since the increase of exhaust backpressure in a WSA is lower compared to conventional DPFs, a WSA essentially has slighter effect on increasing the BSFC.

5. Conclusion

An experimental study was performed to evaluate the effect of a wet soot absorber on reducing the soot emission of a four-cylinder, DI-diesel engine. The test conditions were determined according to the ECE-R49 test cycle. The results revealed that soot removal efficiency occurs best ($\sim$ 70%) under conditions in which the exhaust flow penetrates further into the water and improved mixing occurs between gas and liquid phases. Moreover, the intense bubble break-up, which happens at high gas velocities, can increase the contribution to the particle separation process under high load operating conditions. The comparison between effects of the proposed WSA and conventional DPFs on increasing specific fuel consumption proves the advantage of a WSA over a DPF. This study confirmed the great potential of wet absorbers for agglomeration of diesel particulate matter. Although a removal efficiency of 70% is attained under particular engine operating conditions, higher efficiency is expected by improving the design parameters of the WSA apparatus. Since our current design of WSA is still premature for development by being mounted on a vehicle diesel engines, it is suggested for prospective studies to be concerned about issues such as the performance of a WSA in transient engine operation, increasing the exhaust-water interaction area by changing the geometry of the exhaust gas distributor, and avoiding a partial mist forming in the exhaust gases after being treated by WSA.

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