

A feasibility study on the exhaust-gas treatment efficiency of a wet-scrubber system equipped in a diesel engine: A focus on smoke emission

Nguyen Trung Kien, Vu Duc Manh^{*}, Le Tien Duong, Pham Xuan Phuong

Institute of Vehicle and Energy Engineering, Le Quy Don Technical University

^{*}Corresponding author: manhv@lqdtu.edu.vn

Received 8 Apr. 2023; Revised 31 May 2023; Accepted 12 Jul. 2023; Published 25 Aug. 2023.

DOI: <https://doi.org/10.54939/1859-1043.j.mst.89.2023.153-159>

ABSTRACT

A feasibility examination was conducted on a wet-scrubber system designed in this study to investigate the exhaust gas treatment efficiency of a wet-scrubber system equipped with a diesel engine. This preliminary investigation limits to evaluate the feasibility of the wet scrubber system in decreasing smoke. The influence of multiphase flow configuration in wet-scrubbing aftertreatment systems on emission formation is an interesting topic in the field of exhaust gas aftertreatment. It is our initial attempt to investigate the influence of multiphase flow configuration in a wet-scrubbing hybrid aftertreatment system on key pollutants emitted from Diesel engines in the future. This wet scrubber works by spraying water into the exhaust gas stream. The engine was tested at three-speed conditions (1,500 rpm, 1,800 rpm, and 2,000 rpm, respectively) while varying its torque from 15 to 30 N.m. The results show that under these operating conditions, the smoke level after the scrubber decreases by up to 50%. Please note that only fresh water was used in this study, and the impact of catalysts that could further decrease exhaust gas pollution will be investigated in future studies. The water droplets serve as a medium for capturing and collecting the soot particles present in the exhaust gas. Through collisions, the water droplets cause the soot particles to adhere to their surfaces, a process known as impaction. Additionally, the larger water droplets can facilitate coagulation or agglomeration of the particles, resulting in their enlargement and enhanced capture efficiency.

Keywords: Engine exhaust gas; Exhaust gas after-treatment; Wet scrubber.

1. INTRODUCTION

Compression ignition engines have been traditionally powered by fossil diesel, but the increasing environmental regulations on emissions have led to the adoption of alternative fuels such as compressed natural gas (CNG), liquefied natural gas (LNG) and biofuels [1, 2]. These alternative fuels generally have lower sulfur and particulate emissions compared to traditional fossil counterparts, resulting in reduced air pollution. However, the use of alternative fuels alone may not be enough to meet the stringent emission regulations. Wet scrubbers are widely used in the marine industry to treat exhaust gas and reduce emissions of sulfur oxides (SO_x), nitrogen oxides (NO_x), HC, and particulate matter. This system may also prove useful for treating exhaust gas from generators and/or engines operating in environments with limited airflow, such as underground mines or basements.

Wet scrubbers are typically classified as low-energy scrubbers, which generate large liquid surfaces to interact with gas. Wet scrubbers work by spraying water with or without chemical additives into the exhaust gas stream, which reacts with the pollutants to neutralize them [3, 4]. The influence of multiphase flow configuration in wet-scrubbing hybrid aftertreatment systems on emission formation is a topic of significant research interest in the field of diesel engine emissions and aftertreatment. Multiphase flow refers to the simultaneous presence of two or more phases, such as a liquid and a gas, within a system. In the context of wet-scrubbing hybrid aftertreatment systems, multiphase flow refers to the flow of exhaust gases mixed with a scrubbing liquid through the system [5]. When utilizing wet scrubbers, the type of fuel used can

have a significant effect on the performance and efficiency of the scrubber system. For example, the lower sulfur content in LNG can result in reduced sulfur oxide emissions, but it also reduces the reaction efficiency of the scrubber system. On the other hand, biofuels have different combustion characteristics compared to fossil fuels, and the scrubber system may need to be adjusted to handle the different exhaust gas composition. The use of alternative fuels in marine engines and the utilization of wet scrubbers for exhaust gas treatment have both had a significant impact on reducing emissions from the shipping industry. However, it is important to consider the compatibility between the fuel and scrubber system and to make necessary adjustments to ensure optimal performance and compliance with emission regulations.

One example is using the scrubbing aftertreatment systems in marine engines that operate through the interaction of multiple flows. The hot exhaust containing toxic gases is neutralized through interaction with either a gaseous flow (dry scrubbing) or a liquid flow (wet scrubbing). Wet scrubbers often use seawater or freshwater with or without catalysts [6]. Hybrid scrubbers can use either seawater or freshwater and operate in either open-loop or closed-loop modes [6]. Wet and dry-heat scrubbers are the most commonly used systems for reducing marine engine exhaust temperatures [7]. Wet scrubbers are effective at reducing both NO_x and SO₂ emissions from marine engine exhaust while also lowering the exhaust temperature and quenching flames and sparks at an acceptable engine back pressure.

Studies [8-10] have shown that the configuration of the multiphase flow in the wet-scrubbing hybrid aftertreatment system can significantly affect the efficiency of the system in reducing emissions. Different flow patterns, such as bubbly, dispersed, and annular flows, can have a significant impact on the mass transfer and reaction kinetics within the system. Bubbly flow, for example, can lead to large fluctuations in the concentration of pollutants and reduced mass transfer efficiency, while dispersed flow can increase the overall surface area for mass transfer and improve the reaction kinetics.

In the current literature, there are two main groups of studies on scrubbing systems used in marine vessels: (i) those that focus on fundamental systems using pure reference gases as inputs (SO_x, NO_x) and exclude the engines [11, 12], and (ii) those that directly examine the neutralizing efficiency using engine testbeds or ongoing ships [13]. Group (i) has the advantage of well controlling the input toxic components and catalyst types and concentrations, and it is useful for developing models to describe emission formations. However, engine testbeds can provide a more practical examination of the conditions. Although the multiphase flow arrangements and liquid-gas interactions in wet scrubbers are known to directly affect the exhaust treatment efficiency, there is a lack of studies on this topic.

This study focuses on particulate matter (PM) emission, and it is notable that some terminologies are used to refer to this pollutant, including black carbon, soot, PM, VOC, PAHs, AL, and smoke number. Black carbon is the non-volatile carbonaceous engine exhaust particles that are associated with a complex mixture of organic compounds. The terms "black carbon" and "soot" are commonly used interchangeably in the technical community, however, their phenomena are often inconsistent, sometimes meaning particulate, sometimes meaning a non-volatile or insoluble particulate, and sometimes meaning just a carbonaceous fraction. The following definition probably helps to clarify: soot, a main component of engine particles, consists of black carbon (non-volatile) and volatile organic compounds (VOC) (including primarily polycyclic aromatic hydrocarbons (PAHs) and aliphatic hydrocarbons (AL)).

The smoke number is a measure of the amount of soot or smoke emitted from diesel engines. It is used to evaluate the level of particulate matter emissions from diesel engines, which can have negative effects on air quality and human health. Smoke number measurements can be used to assess the effectiveness of diesel engine emission control systems, such as diesel particulate

filters (DPFs) or diesel oxidation catalysts (DOCs), in reducing particulate matter emissions. Smoke number measurements are typically performed using a smoke meter, such as the testo-308 used in this study. In this study, smoke number measurements were used to evaluate the effectiveness of the scrubbing system designed to reduce soot emissions.

In this study, an experimental system was developed to investigate the exhaust gas treatment efficiency of a wet scrubber system used in diesel engines. This feasibility study focuses on the effectiveness of reducing smoke when utilizing the scrubber, and only fresh water was used in this study. This is our initial attempt to investigate the influence of multiphase flow configuration and the catalysts in a wet-scrubbing hybrid aftertreatment system on emission treatment efficiency in the future.

2. Experiment description

The experiment was carried out on an engine testbed equipped with various measurement tools. Engine load and speed were controlled using an electric brake (#4), as depicted in figure 1.

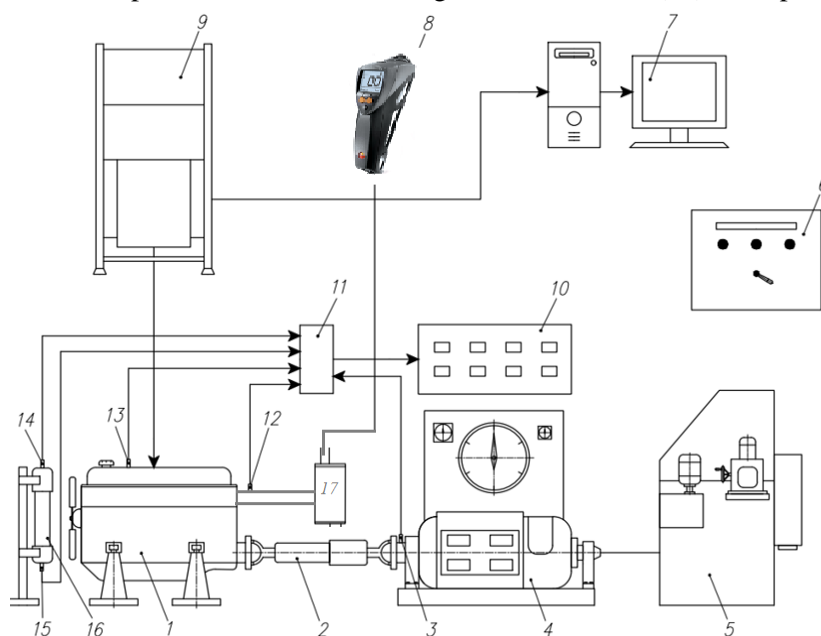


Figure 1. Schematic of experiment system:

1. Diesel engine; 2. Driveshaft; 3. Encoder; 4. Electric brake; 5. Liquid resistor; 6. Controller;
7. Computer; 8. Exhaust analyser (Testo-308); 9. AVL-733S Fuel Balance;
10. Indication and control panel; 11. Connecting box; 12. Exhaust gas thermocouple;
13. Lubricant oil thermocouple; 14 & 15. Inlet and outlet cooling water thermocouples;
16. Radiator; 17. Wet scrubber.

Fuel consumption was measured using an AVL-733S Fuel Balance (#9). Engine torque and speed were continuously recorded using a LabVIEW code. The wet scrubber (#17, as shown in figure 1 and figure 2b) sprays water into the exhaust gas stream, which reacts with pollutants to neutralize exhaust gases. Exhaust gases before and after passing through the wet scrubber were monitored using an E-8500 Plus exhaust analyzer (#8) and a possible smoke tester (Testo-308) to measure the smoke level. In this study, only the smoke number measured using the Testo-308 will be reported. The resulting measurements will be analyzed to evaluate the scrubber's treatment efficiency. It should be noted that not all of the equipment shown in figure 1 may be utilized in this feasibility study. The entire system is presented as a reference, showcasing its full capacity for future investigations. Figure 2 displays a photo of the Testo-308 and a schematic of

the wet scrubber that was developed in this study. Figure 2b illustrates the gas-liquid multiple flow arrangement. The wet scrubber is a closed-loop system that neutralizes hot exhaust containing toxic gases by interacting with the liquid flow through a process known as wet scrubbing. Catalysts were not tested in these preliminary tests.

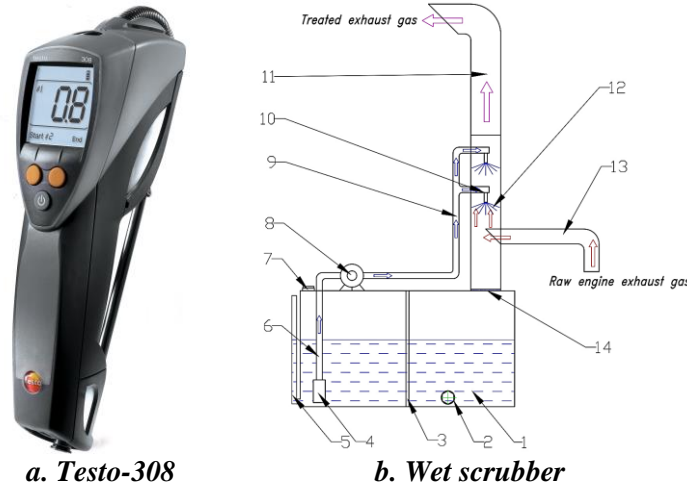


Figure 2. Schematic of experiment system:

- a. Testo-308; b. Configuration of the wet scrubber (item #17 shown in figure 1).
 1. Liquid tank; 2. Drain plug; 3. Separated plate; 4. Filter; 5. Liquid level observation;
 6. Liquid tube; 7. Cap; 8. Electric pump; 9. Liquid tube; 10. Connectors; 11. Injectors;
 12. Reaction chamber; 13. Scrubber-engine exhaust pipe connector; 14. Filter.

The engine was tested at 1,500 rpm, 1,800 rpm, and 2,000 rpm of engine speed while varying its torque from 15 to 30 N.m. A speed of 1,500 rpm is a typical operating condition for electric generators. 1800 rpm is the rated speed of the engine tested. For this preliminary study, these testing conditions are sufficient for our initial effort to examine the feasibility of the treatment system. The conditions are summarized in table 1. For each measurement, the engine was maintained under the stationary conditions listed in table 1, and the measurement was conducted following the Testo-308 operating procedure. Each measurement was performed for a duration of 30-60 seconds during each stationary condition of the engine.

Table 1. Engine testing condition.

Modes	Speed (rpm)	Torque (N.m)
1	1,500	15, 20, 25 & 30
2	1,800	15, 20, 25 & 30
3	2,000	15, 20, 25 & 30

3. RESULTS AND DISCUSSION

Smoke levels were measured by the Testo-308 before and after the scrubber and were analyzed to obtain the reduction fraction shown in figure 3 versus engine torque. The results clearly indicate that the scrubber significantly decreases smoke levels across all engine conditions investigated in this study, with a reduction fraction ranging from 35% to 50%. This demonstrates the high smoke treatment efficiency of the scrubber. However, as engine torque increases, the efficiency decreases significantly. This is expected because the exhaust flow rate increases with engine torque. In this study, a constant liquid flow rate was used, which suggests that the gas-to-liquid interaction decreases with engine torque. Therefore, adding a function to adjust the scrubber's liquid flow rate with torque may improve its smoke treatment efficiency,

especially at high engine loading fractions. When considering the interaction between water and soot in the scrubber, the wet scrubber's mechanism of impaction, coagulation, and capture effectively eliminates soot particles from the engine exhaust. As the soot enters the scrubber, which contains water, it gets rapidly cooled down and quenched. The water droplets serve as a medium for capturing and collecting the soot particles present in the exhaust gas. Through collisions, the water droplets cause the soot particles to adhere to their surfaces, a process known as impaction. Additionally, the larger water droplets can facilitate coagulation or agglomeration of the particles, resulting in their enlargement and enhanced capture efficiency.

This finding is in a good agreement with a previous report [14] that examined the use of a condensational growth-assisted venturi scrubber for controlling soot particle emissions. Based on experimental evidence, it is suggested in [14] that the adsorption of water molecules on the soot surface overcomes the effects of hydrophobicity and line tension. This promotes the condensation of water on the soot surface, resulting in a higher nucleation rate, even under low supersaturation conditions.

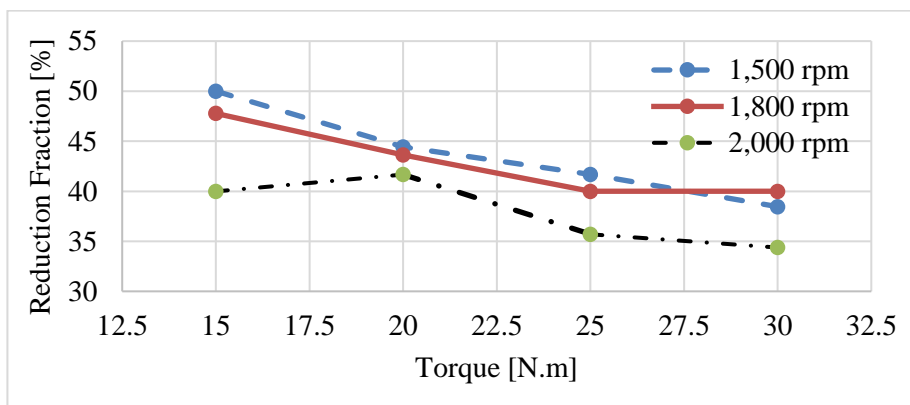


Figure 3. Smoke number versus engine torque.

Figure 4 shows the smoke reduction ratio versus engine speed, which was used to assess the smoke treatment efficiency. The results demonstrate that engine speed has a significant impact on treatment efficiency, with higher engine speeds resulting in lower efficiency. This can be attributed to the increase in exhaust gas velocity with engine speed, which decreases the gas-to-liquid interaction. This highlights the importance of gas-liquid interaction time in neutralizing exhaust gas pollutants. Further investigations are necessary to examine the role of gas-liquid interaction time for other exhaust concentrations, including HC, NO_x, and CO₂.

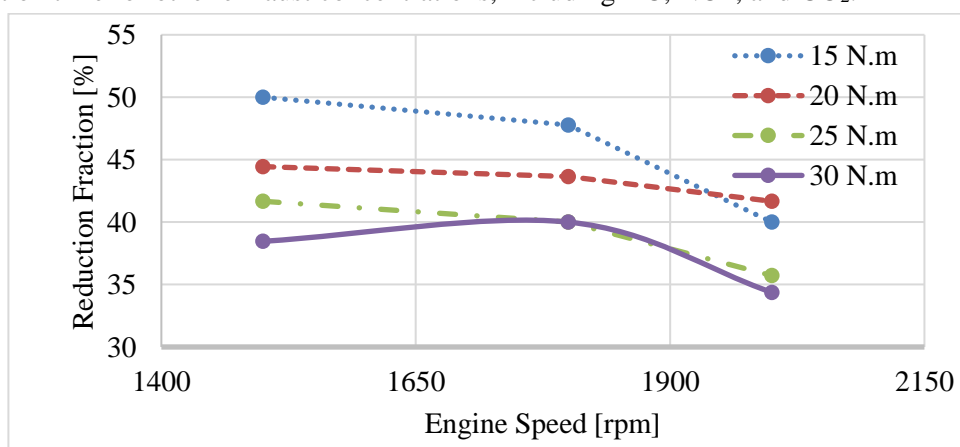


Figure 4. Smoke number versus engine speed.

4. CONCLUSIONS

In this study, an experimental system was developed to investigate the efficiency of a wet-scrubber system installed in a diesel engine in treating exhaust gases. The scrubber system sprays water downward into the exhaust gas flow to decrease pollutant levels before releasing them into the atmosphere. Smoke levels were monitored before and after the scrubber using a Testo-308 device to evaluate its treatment efficiency.

Our initial attempt is to investigate the influence of the multiphase flow configuration in a wet-scrubbing hybrid aftertreatment system on emission formation from a diesel engine in the future. The engine was tested at three speed conditions (1,500 rpm, 1,800 rpm, and 2,000 rpm, respectively), while varying its torque from 15 to 30 N.m. The results show that under these operating conditions, the smoke level after the scrubber decreased by up to 50%. Investigating gas-to-liquid flow arrangements and/or catalysts in the scrubbing liquid could help improve treatment efficiency. Therefore, further research in these topics may be useful.

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TÓM TẮT

Nghiên cứu hiệu quả của bộ xử lý khí thải kiểu scrubber ướt lắp trên động cơ diesel

Bài báo nghiên cứu đánh giá hiệu suất xử lý khí thải cho bộ xử lý khí thải kiểu scrubber ướt được chế tạo để trung hòa các chất gây ô nhiễm của động cơ diesel. Hệ thống scrubber và hệ thống thử nghiệm đã được thiết kế, chế tạo và lắp đặt để khảo sát hiệu quả xử lý khí thải của hệ thống lọc khí ướt được lắp đặt trong động cơ diesel hạng nặng. Hệ thống scrubber ướt này hoạt động bằng cách phun nước vào dòng khí thải để trung hòa các chất gây ô nhiễm. Ảnh hưởng của cấu hình dòng chảy đa pha trong hệ thống xử lý kiểu scrubber ướt đối với sự hình thành khí thải là một chủ đề được quan tâm nghiên cứu trong lĩnh vực phát thải trong đó có động cơ diesel. Nghiên cứu này đánh giá tính khả thi của thiết bị trong việc giảm các loại khí thải chính như NOx, khói và HC. Bài báo này trình bày về hiệu quả xử lý khói từ động cơ diesel khi sử dụng bộ scrubber. Đây là nỗ lực ban đầu để nghiên cứu tổng thể ảnh hưởng của cách bố trí dòng chảy đa pha trong hệ thống đến hiệu quả của việc xử lý khí thải từ động cơ Diesel trong đối với các loại khí thải. Động cơ đã được thử nghiệm ở các chế độ tốc độ 1,500; 1,800 và 2,000 vòng/phút, đồng thời thay đổi mô-men xoắn từ 15 đến 30 N.m. Kết quả cho thấy, ở điều kiện vận hành này, độ khói sau bộ xử lý khí thải giảm tới 50%, HC. Điều này là do sự tương tác giữa khí thải và dòng chất lỏng bên trong thiết bị scrubber. Xin lưu ý rằng nghiên cứu này chỉ sử dụng nước mà chưa đánh giá tác động của các chất xúc tác đến việc xử lý ô nhiễm. Vấn đề này sẽ được nghiên cứu chi tiết trong tương lai.

Từ khoá: Khí thải động cơ; Xử lý khí thải; Scrubber ướt.