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DESIGN DEVELOPMENT FOR CENTRIFUGAL DIESEL PARTICULATE ARRESTOR

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ABSTRACT

The aim of this paper is to introduce a design of Centrifugal Diesel Particulate Arrestor with better efficiency and lower cost. The design was theoretically modeled and experimentally verified. A commercial Diesel Particulate Arrestor was selected for comparison in terms of embers collection efficiency theoretically and then verified experimentally. Also, the pressure drop for the new designed Diesel Particulate Arrestor and the commercial one was compared experimentally. The theoretical modeling of collection efficiency was carried out using Computational Fluid Dynamics (CFD) and Particle Tracing for Fluid Flow modules based upon the Reynolds-Averaged Navier Stokes (RANS) equations and the Newton's Second Law. The two Diesel Particulate Arrestors performances were measured according to Standard BS EN 1834-3:2000 through a special designed test rig. Three different flow rates were selected for the experimental verifications to simulate the real engine flow rates at different engine loads. As in terms of large particles collection efficiency, the new designed Arrestor is better than the commercial one by 13.6% and in terms of pressure drop shows lower pressure drop than the commercial one by 89.8%. In terms of cost the new designed Arrestor is cheaper than the commercial one by 37%.

Keywords: spark arrestors, spark arrestors optimization, diesel particulate arrestor.

1. INTRODUCTION

Sparks and embers which are produced from Diesel Engines could lead to fire and explosion if they touched flammable materials. Inconvenient design, inappropriate maintenance, and misunderstanding of risks may lead to fire and explosion [1].

These sparks are produced as a result of incomplete reaction of the fuel which produces extra deposited carbons. These carbons are deposited inside the diesel engine combustion chambers and the exhaust system which then broken into small particles and burnt as a result of the exhaust high temperature.

Diesel Particulate Arrestors are devices used to trap these sparks and embers. The necessity for Diesel Particulate Arrestors was established with the introduction of wood burning locomotives in1919, and they were first applied in the form of a wire netting cap placed over the top of the smokestack [2]. The standard procedures for testing Arrestors started in 1968, which was published by Society of Automotive Engineers (SAE) and it was continuously developed until its final version in 1991 [3]. Also, the British Standard (BS) created a method for testing the Arrestors which was published in 2000 [4].

The aim of this study is to introduce a design of Diesel Engine Particle Arrestor with better efficiency and lower cost [5].

2. THEORETICAL BACKGROUND

There are five main methodologies that are used in arresting Sparks Particulate namely; Particles Impact, Refinery Meshing, Electrostatic Charge, Particles' Grinding, and Centrifugal Force [6]. This paper focuses on Diesel Particulate Arrestor Centrifugal Type which will be studied focusing upon three main affecting categories; turbulent flow, collection efficiency, and pressure drop.

2.1 Centrifugal Force Methodology

In this methodology, stationary baffles are used to remove the ashes or embers from the exhaust gas by centrifugal force.

2.1.1 Factors affecting the type of flow

Exhaust gas turbulent flow shall be increased to reduce the temperature of sparks that results in eliminating fire. As the turbulent flow increases, Reynolds numberReincreases [6].

$$Re = \frac{\rho v D_H}{\mu} = \frac{v D_H}{\nu} = \frac{Q D_H}{\nu A} \quad (1)$$

ρ is the fluid density (kg/m³).
ν is the fluid kinematic viscosity ($\nu = \frac{\mu}{\rho}$)(m²/s).
D_H is the pipe hydraulic diameter (m).
μ is the fluid dynamic viscosity (Pa·s or N·s/m² or kg/(m·s)).
v is the mean velocity of the object relative to the f luid (SI units: m/s).
Q is the volumetric flow rate (m^3/s).
A is the cross-sectional area of the pipe (m²).
Turbulent flow occurs when Re>4000.

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2.2 Theoretical Modeling of Diesel Particulate Arrestors' Collection Efficiency

Computational Fluid Dynamics (CFD) and Particle Tracing for Fluid Flow modules based upon Newton's Second Law is used in calculating the Arrestors' collection efficiency which is available in COMSOL Multiphysics software using finite element analysis with adaptive meshing and error control using several numerical solvers [7].

In this paper, the collection efficiency of the Diesel Engine Particle Arrestorsis calculated using both Computational Fluid Dynamics (CFD) and Particle Tracing for Fluid Flow modules [7].

The fluid turbulence model [7], is used in solving turbulent kinetic energy *k*, and the dissipation per unit turbulent kinetic energy *ω* (also known as the specific dissipation rate). The CFD Module has the Wilcox revised *k-ω* model.

$$\rho\frac{\partial k}{\partial t} + \rho u.\nabla k = P_k - \rho\beta^* k\omega + \nabla.((\mu + \sigma^*\mu_T)\nabla k) \quad (2)$$

The turbulent kinetic energy unit is m^2/s^2. It can be defined as:

$$k = \frac{1}{2}(\mathrm{mean}(u'^2) + \mathrm{mean}(v'^2) + \mathrm{mean}(w'^2)) \quad (3)$$

Where *u'*, *v'*, and *w'* are the three fluctuation components of velocity.

$$\rho\frac{\partial \omega}{\partial t} + \rho u.\nabla\omega = \alpha\frac{\omega}{k}P_k - \rho\beta\omega^2 + \nabla.((\mu + \sigma\mu_T)\nabla\omega) \quad (4)$$

As the specific dissipation rate *ω*, is the rate at which turbulence kinetic energy is converted into thermal internal energy per unit volume and time. The specific dissipation rate unit is 1/s. It can be defined as:

$$\omega = \frac{\varepsilon}{k\beta^*} \quad (5)$$

Where *ε* is known as turbulence dissipation and β^* is known as model constant.

$$\mu_T = \rho\frac{k}{\omega} \quad (6)$$

μ_T is the eddy viscosity, *ρ* is the density, *u* is velocity vector, P_k is the net production per unit dissipation of *k*, and

Standard values for the model constants are:

$$\alpha = \frac{13}{25}, \beta = \beta_0 f_\beta, \beta^* = \beta_0^* f_\beta,$$
$$\sigma = \frac{1}{2}, \sigma^* = \frac{1}{2}, \beta_0 = \frac{13}{125}$$
$$f_\beta = \frac{1 + 70x_\omega}{1 + 80x_\omega}, x_\omega = \left|\frac{\Omega_{ij}\Omega_{jk}S_{ki}}{(\beta_0^*\omega)^3}\right|$$

$$\beta_0^* = \frac{9}{100}, f_{\beta^*} = \begin{cases} 1, & x_k < 0 \\ \frac{1+680x_k^2}{1+400x_k^2}, & x_k \geq 0 \end{cases} \quad (7)$$

$$x_k = \frac{1}{\omega^3}(\nabla k.\nabla\omega) \quad (8)$$

Where in turn Ω_{ij} is the mean rotation-rate tensor

$$\Omega_{ij} = \frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right) \quad (9)$$

$$S_{ij} = \frac{1}{2}\left(\frac{\partial\bar{u}_i}{\partial x_j} + \frac{\partial\bar{u}_j}{\partial x_i}\right) \quad (10)$$

and S_{ij} is the mean strain-rate tensor

As the strain rate is a measure of how fast the three velocity components change in each of the three directions.

$$P_k = \mu_\tau\left(\nabla u:(\nabla u + (\nabla u)^T) - \frac{2}{3}(\nabla.u)^2\right) - \frac{2}{3}\rho k\nabla.u \quad (11)$$

The Particle Tracing Module[7] allows to track the trajectories of the particles under an external force, and the particles number that pass through a target place.

These particles momentum come from Newton's second law, which states that the net force on a particle is equal to its time rate of change of its linear momentum in an inertial reference frame:

$$\frac{d}{dt}(m_p v) = F_D + F_g + F_{ext} \quad (12)$$

Where F_D is the drag force which is defined as:

$$F_D = \left(\frac{1}{\tau_p}\right)m_p(u - v) \quad (13)$$

Where m_p is the particle mass in kg, τ_p is the particle velocity response time in second, *v* is the velocity of particle in m/s, *u* is the fluid velocity in m/s, F_g is the gravitational force vector in N, and F_{ext} is any other external force in N.

When turbulent dispersion is activated, the fluid velocity used in the drag force becomes:

$$u = U + u' \quad (14)$$

Where *U* is the mean velocity and *u*' is the turbulent fluctuation, defined as:

$$u' = \xi\sqrt{\frac{2k}{3}} \quad (15)$$

Where *k* is the turbulent kinetic energy. The quantity ξ is a normally distributed random number with zero mean and unit standard deviation.

The gravity force is given by;

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$$F_g = m_p g \frac{(\rho_p - \rho)}{\rho_p} \qquad (16)$$

Where ρ is the density of the surrounding fluid in kg/m^3 and g is the gravity vector, ρ_p is the particle density in kg/m^3 and m_p is the particle mass.

3. DESIGN AND MODELING

This part shows the configurations, and the working theory for the commercial Diesel Particulate Arrestor and the new designed one.

3.1 Commercial Diesel Particulate Arrestor of Centrifugal Collection Type

Commercial Diesel Particulate Arrestors in Figure-1 and Figure-2 are of centrifugal collection type according to standard BS EN 1834-3:2000[4].

The flow carrying particles will pass through three chambers as a result of the inlet deflection blades; some of these particles will stay outside the Arrestor. As most of the particles will be trapped in the second and third chambers due to centrifugal force that affects particles. This centrifugal force results from exhaust gas rotation due to the inclined blades fixed at each slot opening of the Arrestor part ends as in Figure-1. Also, part of the particles that reached the outlet will be impeded by the outlet deflection blades.

This Diesel Particulate Arrestor consists of inlet pipe 50 mm, two inlet deflection blades, expansion chamber of diameter 152 mm and of length 445 mm, two internal plates with middle hole of 116 mm, two outlet deflection blades, outlet pipe 50 mm, and Arrestor part that consists of pipe of diameter 115mm and length 360mm. This Arrestor part is closed by a plug at its outlet end. It has slots with inclined blades of length 80mm and opening height 2mm which are distributed around the Arrestor circumference at its two ends which cause air or the exhaust gas to be rotated. Also, at the middle of its length, it has slots of length 47 mm and of height 2 mm.

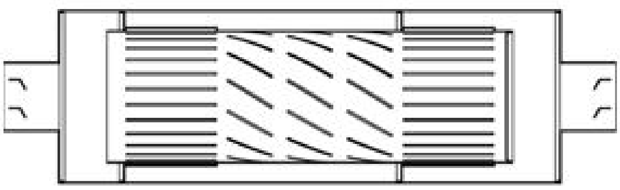

Figure-1. Schematic drawing of commercial diesel particulate arrestor.

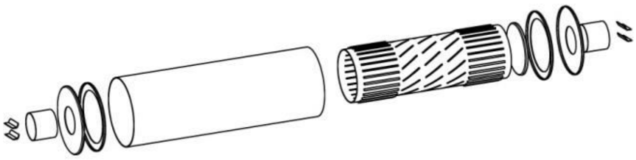

Figure-2. Commercial diesel particulate arrestor sub assembly.

3.2 Designed Diesel Particulate Arrestor

The proposed design of the Diesel Particulate Arrestor is of centrifugal collection type according to standard BS EN 1834-3:2000 [2]. This Particle Arrestor consists of Inlet pipe of diameter 76 mm and length 75 mm, Expansion chamber of diameter 200 mm and length 300 mm, Internal perforated plate, Outlet pipe of 76 mm, and Diesel Particulate Arrestor part of ten ribs and each rib contains a slot of 2 mm height and 160 mm length. Through this design; inclined blades that are fixed at each slot opening of the Arrestor part, would generate centrifugal force. The flow carrying particles will pass to the first chamber which will be affected by the centrifugal force. Then these particles will be trapped before passing to the second chamber as a result of particles weight and the perforated plate number 2, see Figure-3 and Figure-4.

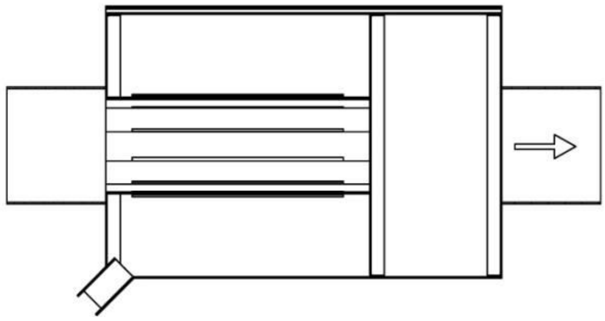

Figure-3. Schematic drawing for the new designed diesel particulate arrestor.

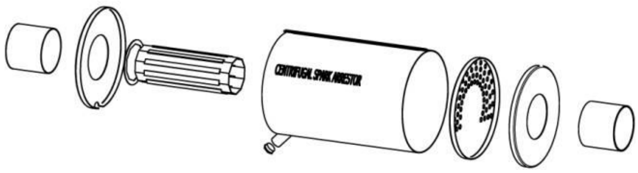

Figure-4. The New Designed Diesel Particulate Arrestor Sub Assembly.

3.3 Simulation Modeling of Diesel Particulate Arrestors' Collection Efficiency

COMSOL Multiphysics is used in simulating the collection efficiency of the Diesel Particulate Arrestors. In this software, the type of flow, the air flow rates, the particle sizes, and the particles weights is specified according to the standard BS EN 1834-3:2000and the diesel engine power rate which is 38 kWm. The flow rates used in simulation are 0.09, 0.10 and 0.12 m^3/s. The particle sizes used in simulation is 0.2 and 0.5 mm. The carbon powder weights used in simulation is 62.6 g, 73.7 g and 85.7 g. Each particle size shall be injected in each flow rate, so each Diesel Particulate Arrestor has 6 models on COMSOL Multiphysics.

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4. EXPERIMENTAL WORK

4.1 Diesel Particulate Arrestor Collection Efficiency

This part discusses the test methodology, test rig and procedure of obtaining the Diesel Particulate Arrestor collection efficiency.

The technique used in this test was adopted by the standard BS EN 1834-3:2000 [4]. A testrig was built with the following components, see Figure-5 and Figure-6:

a) Blower.

b) Particles feeder.

c) Flow meter.

d) Tested Diesel Particulate Arrestor.

e) Filter for collecting the test particles that have passed through the Arrestor.

For determining the collection efficiency (the percentage of the mass of the collected particles related to the mass of the injected particles) of the Diesel Particulate Arrestor, test particles were injected into the air stream. The test particle sizes were 0.1, 0.2 and 0.5mm and have an apparent density of 900 kg/m^3. The test particles were injected at a uniform rate into the air stream for about 1 minute with an accuracy of ±5 %. The collection efficiency at each flow rate and each particle size were determined by at least one measurement.

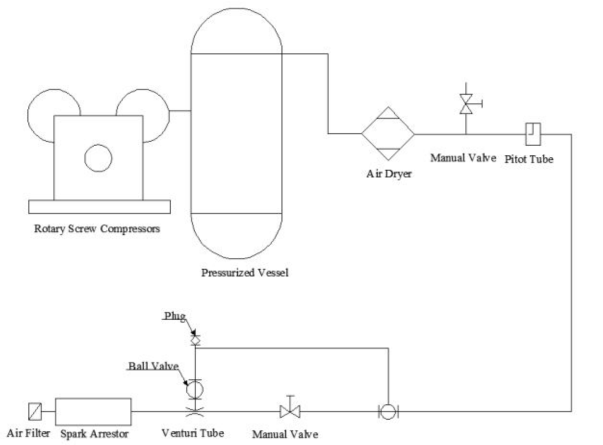

Figure-5. Schematic diagram of diesel particulate arrestor test apparatus.

Figure-6. Portion of real diesel particulate arrestor test apparatus.

In this experiment, three flow rates were used; 0.12, 0.10 and 0.09 m^3/s. As the 0.12 m^3/s represent approximately the Engine exhaust flow rate up to 100% of engine load. Two particle sizes 0.5 and 0.2mm were used. Six tests were conducted on each Diesel Particulate Arrestor. As each Diesel Particulate Arrestor was tested with each particle size and flow rate. The mass of the carbon powder was determined according to the flow rate value in each test. As for the first, second and third flow rates, the carbon weight were; 85.7, 73.7 and 62.6 g consequently.

4.2 Diesel Particulate Arrestor Pressure Drop

The pressure drop was measured across the Diesel Particulate Arrestors using digital manometer. This is to avoid introducing high back pressure upon the engine due to adding the Diesel Particulate Arrestor in the exhaust system.

The measurement system of pressure drop is illustrated in Figure-7.

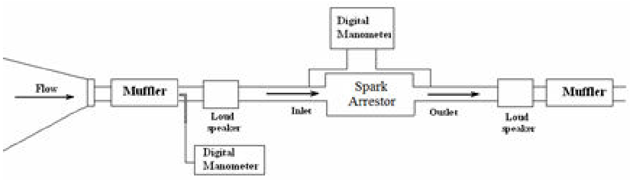

Figure-7. Schematic for Pressure Drop Measuring System.

5. MODELING RESULTS

This part shows the theoretical and the experimental results for the Diesel Particulate Arrestors' collection efficiency, and their simulation error. Also, this part shows the cost and the experimental results for the Diesel Particulate Arrestors' pressure drop.

5.1 Commercial Diesel Engine Particle Arrestor

This part shows the theoretical modeling and the experiments results of the Commercial Diesel Particulate Arrestor and the correlation between them in case of collection efficiency.

5.1.1 Collection efficiency diesel particulate arrestor

For particle size 0.5mm, the Experimental Collection Efficiency (C.E) function of flow rate (q) is

$$C.E = 85.11e^{-0.01q} \quad (17)$$

The simulation mean error difference is about 17.6%, as shown in Figure-8.

For particle size 0.2mm, the Experimental Collection Efficiency function of flow rate is

$$C.E = 96.41e^{-0.01q} \quad (18)$$

with an average error 1.56% higher than the measured results. The simulation mean error difference is about 3.5%, as shown in Figure-9.

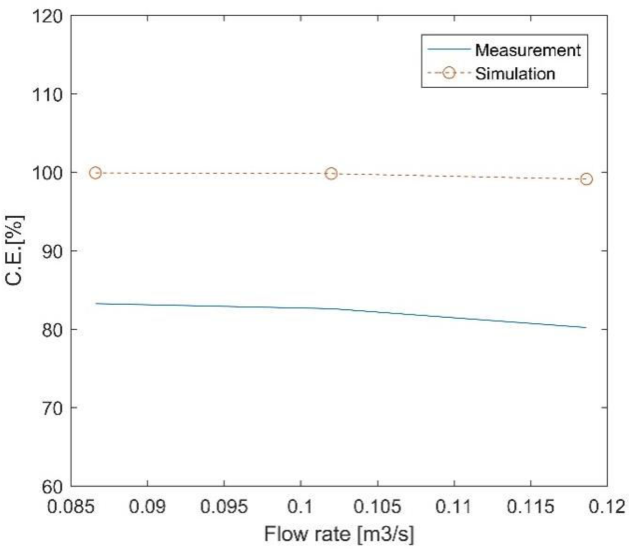

Figure-8. Collection efficiency using particle size 0.5 mm.

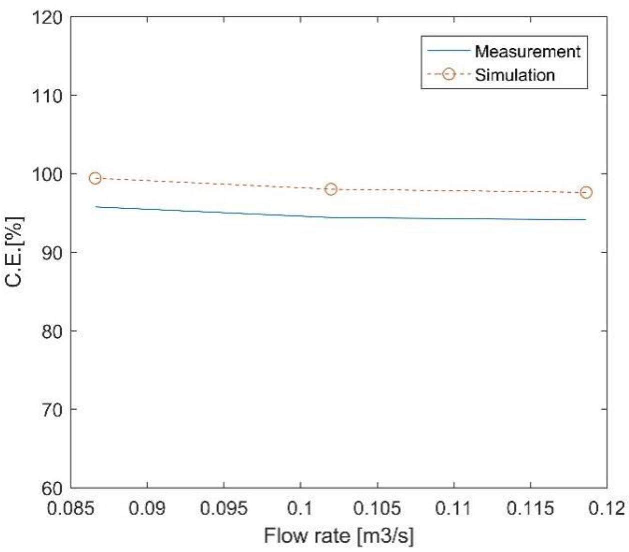

Figure-9. Collection efficiency using particle size 0.2 mm.

This simulation mean errors result from the modifications which were done for modeling of the Diesel Particulate Arrestor in COMSOL Multiphysics which were; the number of louvers that were reduced from 26 × 2slots to 13 × 2 slots, and their areas were increased after the reduction of the slots' number (to keep same total area). This modification was done to reduce the computational complexity using Reynolds-Averaged Navier Stokes (RANS) equations. These modifications were intended to boost computation of COMSOL Multiphysics in indicating the collection efficiency of the Diesel Particulate Arrestor.

5.1.2 Diesel particulate arrestor pressure drop

The Experimental Pressure Drop function of flow speed is

$$\Delta P = 7.427v^2 + 3.088v - 2.581 \quad (19)$$

with an average error 0.012% lower than the measured results shown in Figure-10. This equation can be used to estimate the pressure drop of the commercial Diesel Engine Particle Arrestor at any flow speed.

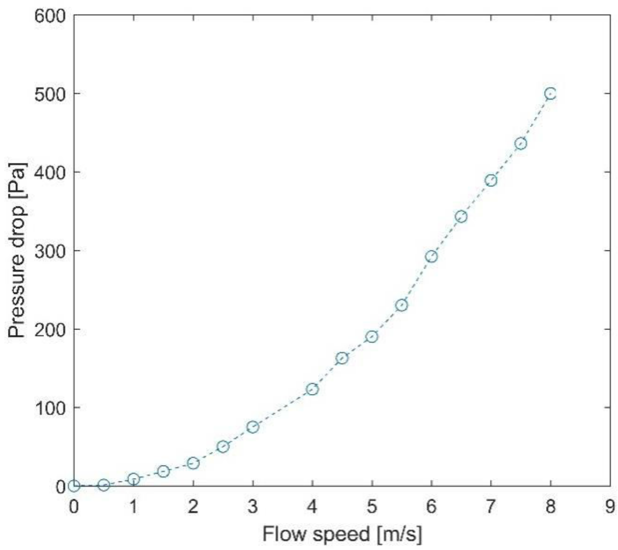

Figure-10. Measured pressure drop commercial diesel engine particle arrestor.

5.2 The New Designed Diesel Particulate Arrestor

This part shows the correlation between the theoretical modeling and the experiment results in case of the collection efficiency and the experimental results in case of pressure drop for the new designed Diesel Particulate Arrestor.

5.2.1 Collection efficiency diesel engine particle arrestor

For particle size 0.5mm, the Experimental Collection Efficiency function of flow rate is

$$C.E = -0.026q^2 + 0.107q + 95.76 \quad (20)$$

With an average error of about 0.085% lower than the measured results. The simulation mean error

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difference is 3.54%, as shown in Figure-11. For particle size 0.2mm, the Experimental Collection Efficiency function of flow rate is

$$C.E = 82.37e^{0.016q} \quad (21)$$

With an average error of about 2.726% lower than the measured results. The simulation mean error difference is about 11%, as shown in Figure-12.

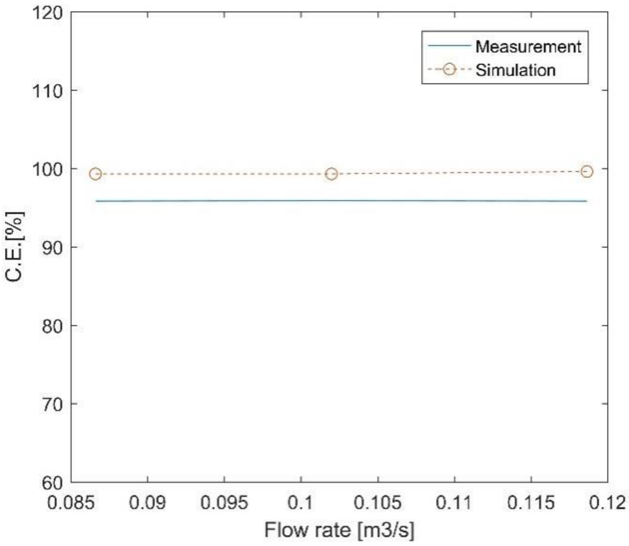

Figure-11. Collection efficiency using particle size 0.5mm.

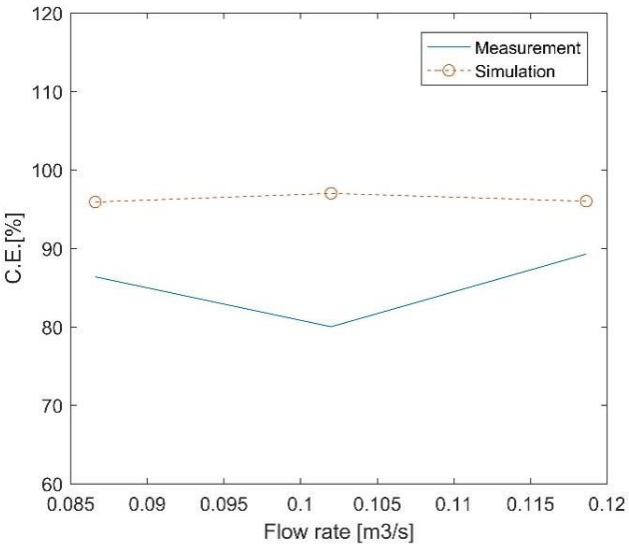

Figure-12. Collection efficiency using particle size 0.2mm.

These simulation errors are due to the modifications that were done in the Diesel Particulate Arrestor model in COMSOL Multiphysics which are; the number of slots that was reduced from 10 slots to 6 slots, and their areas that were increased for compensation. Slots were reduced so as to reduce the computational complexity using Reynolds-Averaged Navier Stokes (RANS) equations to boost computation of Comsol Multiphysics in indicating the collection efficiency of the Diesel Particulate Arrestor.

5.2.2 Diesel particulate arrestor pressure drop

The Experimental Pressure Drop function of flow speed is

$$\Delta P = 0.631v^2 - 0.727v + 8.303 \quad (22)$$

With an average error of about 0.0085% lower than the measured results Figure-13. This equation can be used to compute the pressure drop of The New Designed Diesel Engine Particle Arrestor at any flow speed.

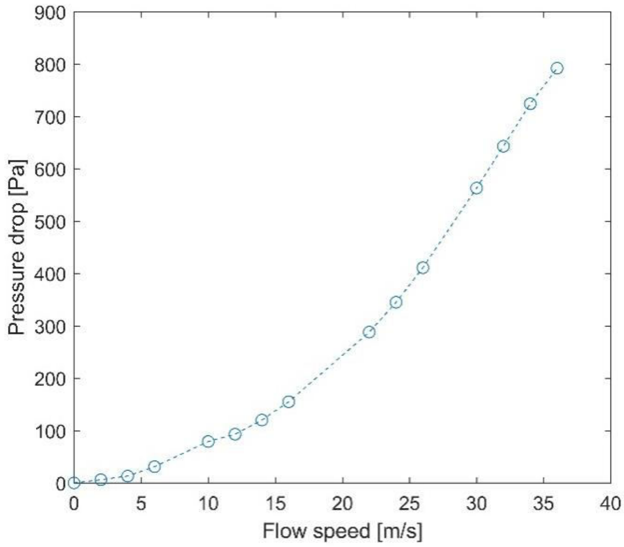

Figure-13. Measured pressure drop for the new designed diesel particulate arrestor.

5.3 Diesel Particulate Arrestor

5.3.1 Comparison results

For the collection efficiency, as the particle size becomes bigger the new designed Diesel Particulate Arrestor shows to have better efficiency, while as the particle size becomes smaller the commercial Diesel Particulate Arrestor shows to have better efficiency, see Figure-14 and Figure-15.

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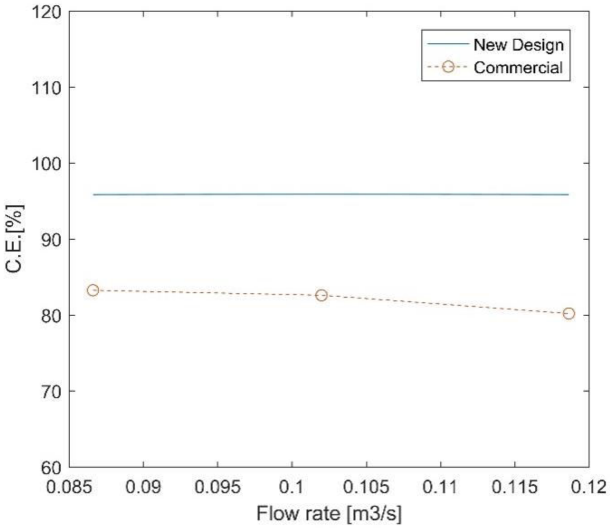

Figure-14. Collection efficiencies comparison at particle size 0.5 mm.

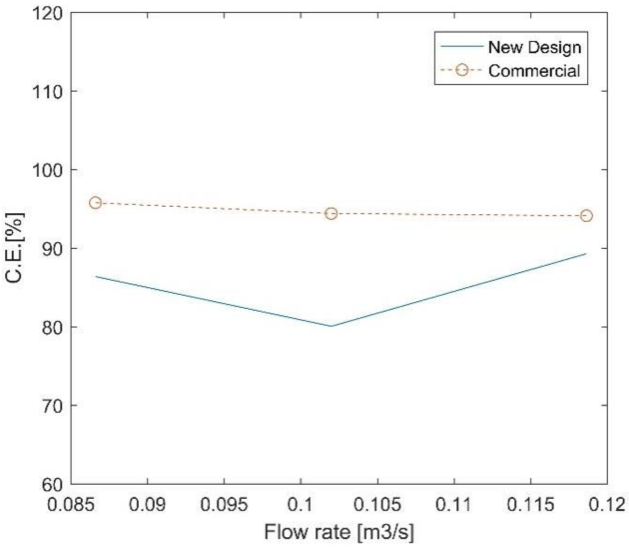

Figure-15. Collection efficiencies comparison at particle size 0.2 mm.

For the pressure drop, the new designed Diesel Particulate Arrestor is shown to be lower than the commercial one, see Figure-16.

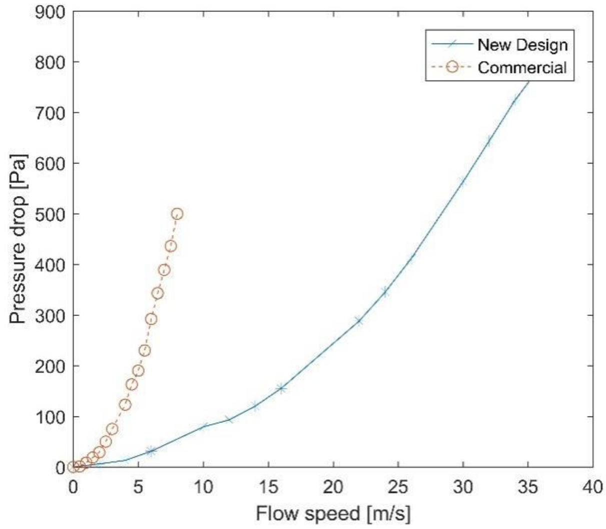

Figure-16. Comparison between diesel particulate arrestors' pressure drop measurement.

6. THE DIESEL ENGINE PARTICULATE ARRESTORS COST

The new designed model aims to minimize the total cost including operations, raw material, and labor time. The following table includes the cost reduction percentage in the operations, raw material and labor time for the new designed Diesel Particulate Arrestor related to the commercial one.

Table-1. The cost reduction percentage for the new designed diesel particulate arrestor.

Operations	Cost Reduction (%) for the New Designed Diesel Particulate Arrestor
Tailoring	21%
Cutting process	40%
Welding Process	47%
Assembly	70%
Material	32%
Painting	12%

7. CONCLUSIONS

The most important characteristic of the Diesel Particulate Arrestors are their collection efficiency. In this paper, a designed model of Diesel Particulate Arrestor was introduced. A comparison was done theoretically and experimentally between the new designed model of Diesel Particulate Arrestor and a commercial one.

Regarding the collection efficiency measurement results for the new designed Diesel Particulate Arrestor, it was shown that the collection efficiency becomes better as the particle size becomes bigger. While the collection efficiency of the commercial Diesel Particulate Arrestor becomes better as the particle size becomes smaller. As a

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result of convection, when a solid particle becomes bigger, the heat transferred from it to the nearest flammable material or fluid becomes bigger, so in this case the new model of Diesel Particulate Arrestor is shown to be better than the commercial one.

The arising pressure drop is an important factor for engines, as high back pressure has a negative effect on engine efficiency resulting in a decrease of power output that must be compensated by increasing fuel consumption. The new designed Diesel Particulate Arrestor shows to have lower back pressure than the commercial one by 89.8%.

The cost of the new designed Diesel Particulate Arrestor was shown to be of lower cost than the commercial one by 37%.Therefore, based on the previous results, the new designed Diesel Engine Particle Arrestor shows to have much better efficiency with lower cost.

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