CFD ANALYSIS ON THE EFFECTS OF EXHAUST BACKPRESSURE GENERATED BY FOUR-STROKE MARINE DIESEL GENERATOR AFTER MODIFICATION OF SILENCER AND EXHAUST FLOW DESIGN

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ABSTRACT

This study is to analyse the exhaust backpressure of older and new exhaust piping design and silencer or muffler position after modification of the exhaust system of a 4-stroke marine diesel generator which operates at Marine Generator Workshop, Ungku Omar Polytechnic, Malaysia. The purpose of the exhaust system modification is to collect the exhaust gases produced inside combustion chamber of the engine cylinders and discharge them as quickly and silently as possible to atmosphere. Generally the better a silencer or muffler is at attenuating sound the more backpressure is generated. In a reactive silencer where good attenuation is achieved, the exhaust gases are forced to pass through numerous geometry changes of exhaust system and a fair amount of backpressure may be generated, which reduces the power output of the engine slightly. However, too much backpressure generated may led the power losses, weakening the engine performance and increased the fuel consumption. Henceforth, the study is aims to find the relationship between the exhaust backpressure levels occurred in exhaust flow design as well as silencer position and yet propose the best design to ensure the optimisation of engine performance. The actual dimensions of the exhaust system is used to perform the computational fluid dynamic (CFD) simulation and analysis. The performance of an exhaust system is based on velocity and exhaust backpressure. Investigation in CFD was performed on four parameters comprises manifold temperature, manifold pressure, exhaust piping system temperature and atmosphere pressure. Results of CFD simulation was showed in the form of pressure and velocity contours and streamline. This study found the modification of exhaust piping design of the 4-stroke marine diesel generator increased the backpressure up to 94.7%.

Keywords: CFD analysis, diesel generator, exhaust backpressure, exhaust muffler, exhaust silencer.\

INTRODUCTION

Internal combustion of four-stroke engine or marine diesel generator are generating the acoustic pulse by the combustion process. This noise is controlled through the use of silencers and mufflers. A silencer generally has been used for noise attenuation devices, while a muffler is smaller than silencer is device designed to reduce engine exhaust noise. Engine exhaust noise is controlled through the use of silencers and mufflers (Burnete, Moldovanu, Baldean, & Kocsis, 2016; Lota, Ravindran, Rao, & Verma, 2014; Shah, Kuppili, Hatti, & Thombare, 2010; Sherekar & Dhamangaonkar, 2014). Exhaust systems of four-stroke engine collect exhaust gases from engine cylinders and discharge them as quickly and efficiently as possible (Gopan & Annamalai, 2015; Pangavhane, Ubale, Tandon, & Pangavhane, 2013). Primary system design considerations includes: 1) minimizing resistance to gas flow (backpressure) and keeping it within the limits specified for the particular engine model and rating to provide maximum efficiency, 2) reducing exhaust noise emission to meet local regulations and application requirements, 3) providing adequate clearance between exhaust system components and engine components, machine structures, engine bays, enclosures and building structures to reduce the impact of high exhaust temperatures on such items, 4) ensuring the system which does not overstress engine components such as turbochargers and manifolds with excess weight because an overstressing phenomena may shorten the life of engine components and 5) ensuring the exhaust system components is able to reject heat energy as intended by the original design (Pangavhane *et al.* 2013).

Exhaust noise is one of the principal noise sources of any engine. The purpose of the silencer is to reduce the noise of the exhaust before it is released to the atmosphere. Exhaust noise arises from the intermittent release of high pressure exhaust gas from the engine, causing strong gas pressure fluctuations in the exhaust system. This leads not only to discharge noise at the exhaust outlet, but also to noise radiation from exhaust pipe and silencer surfaces. A well designed and matched exhaust system will significantly reduce noise from these sources (Sagar & Munjal, 2016). The silencer makes a major contribution to exhaust noise reduction. The required degree of silencing depends on factors such as the application type, whether it is stationary or mobile and whether there are any legal regulations regarding noise emission (Lee & Jang, 2012; Middelberg *et al.* 2003). Normally the silencer is installed on the exhaust piping systems. The function of the exhaust piping is to convey the exhaust gases from the engine exhaust outlet to the silencer and other exhaust system components, terminating at the system outlet. Moreover, the exhaust piping should never be supported directly by the engine block or engine components. Allowances should be made for system movement and vibration isolation by using suitable flexible components such as rubber dampers or springs (Karuppusamy & Senthil, 2013; Kesgin, 2005; Shital, 2010). Piping must be designed with engine service in mind. In many cases, an overhead crane will be used to service the heavier engine components on the larger engines (Pinelli & Bucci 2009). The Figure-1 shows the proper design that should be followed when designing an exhaust piping system.

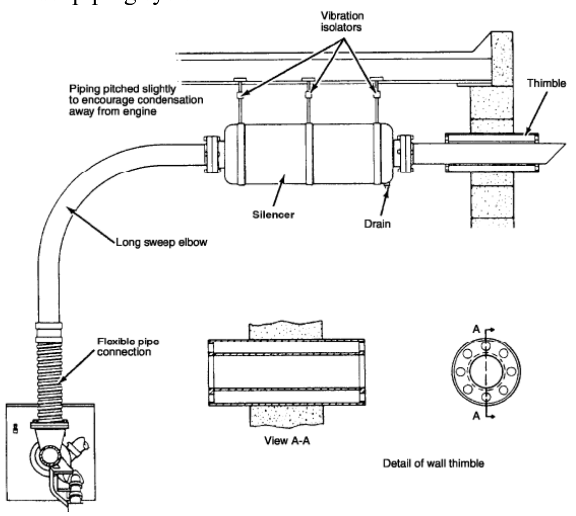

Figure-1. Typical silencer details (Pinelli & Bucci 2009).

Excessive exhaust restriction and backpressure can adversely affect performance, resulting in reduction of output power and increased fuel consumption, exhaust temperatures and emissions. It is imperative that exhaust backpressure is kept within specified limits for those engines subject to emissions legislation (Chaudhari, Pate, Jani, & Bambhania, 2015). When designing an exhaust system, the design target for backpressure should be half the maximum allowable system backpressure. Backpressure includes restrictions due to pipe length, diameter, silencer, exhaust system configuration, rain cap and other exhaust-related components (Balakrishna & Mamidala, 2014; Mittal, Donahue, & Winnie, 2015; Sinuka, Omar, & Makhomo, 2014). To ensure compliance, exhaust system backpressure must be verified to be within the theory and practice in exhaust system design. Hence, exhaust piping should be designed to minimise the exhaust backpressure while keeping engine serviceability in mind.

EXHAUST BACKPRESSURE

Engine exhaust backpressure is defined as the exhaust gas pressure that is produced by the engine to overcome the hydraulic resistance of the exhaust system in order to discharge the gases into the atmosphere (Chaudhari *et al.* 2015). The performance of a silencer is mainly dependent on the values of backpressure. Pressure drop of exhaust system includes losses due to piping, silencer, muffler and termination. A high backpressure is commonly caused by one or more factors such as exhaust pipe diameter too small, excessive number of elbow especially the sharp bends in the exhaust system, exhaust pipe is too long or too high resistance within the silencer and muffler (Lota *et al.* 2014; Pangavhane *et al.* 2013). Backpressure has a significant effect on performance of an engine particularly in diesel generator which is used in this study. The pressure in combustion chamber can be considered atmospheric when the cylinder filling (scavenging) is superimposed to the exhaust phase i.e., with the exhaust port opened to the external atmosphere. The effectiveness of the cylinder filling with fresh charge depends on small differences of pressure, and the engine can only tolerate small amounts of exhaust backpressure (Hield, 2011; Pangavhane *et al.* 2013). Every time the exhaust flow meets a section increase, a negative pressure is generated and propagates in the opposite direction of flow with the speed of sound. In other hands, if the flow finds a restricted section, a positive pressure wave always propagates in the opposite direction with the speed of sound. According to acoustic theory, the propagation of waves depends strictly on the length and section of ducts, volumes, and logically on the speed of sound (Lee & Jang, 2012; Middelberg *et al.* 2003).

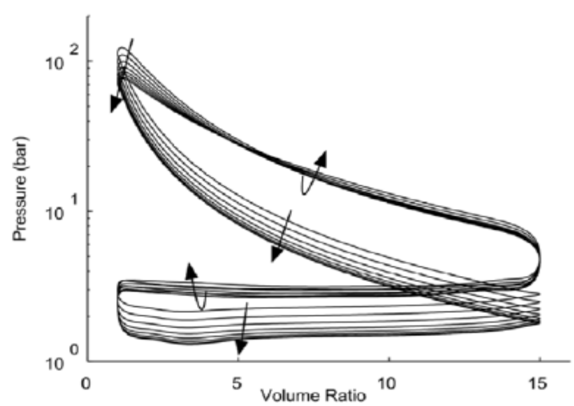

Figure-2. The P-V diagram for a cylinder, for various backpressure. Arrows show direction of change with increasing backpressure (Hield, 2011).

In four stroke engines the most obvious effect is the increase in size of the pumping loop as the backpressure increases due to the extra work done by the piston on the gas in pumping it out of the cylinder during the exhaust stroke as shown in Figure-2. This represents the extra work that must be done by the engine as the backpressure increases in addition to meeting the constant load demand. Although the maximum cycle pressure decreases due to the reduced compressor pressure ratio, the engine pressure ratio remains effectively constant. The gradient of the power stroke curve also decreases with increased backpressure. This is due to the increase in the burn duration that occurs with reduced maximum cylinder pressure (Hield, 2011; Pangavhane *et al.* 2013).

Effects of increased or excessive backpressure

High backpressure can cause a reduction in engine efficiency or increase in fuel consumption, overheating, and may result in a complete shutdown of the engine potentially causing significant damage. At increased backpressure levels, the engine has to compress the exhaust gases to a higher pressure which involves additional mechanical work and/or less energy extracted by the exhaust turbine which can affect intake manifold boost pressure. This can lead to an increase in fuel consumption, PM and CO emissions and exhaust temperature. The increased exhaust temperature can result in overheating of exhaust valves and the turbine (Chaudhari *et al.* 2015). An increase in NOx emissions also may be happened due to the increase in engine loads. Increased backpressure may affect the performance of the turbocharger, causing changes in the air-to-fuel ratio-usually enrichment which may be a source of emissions and engine performance problems. Besides, it may also prevent some exhaust gases from leaving the cylinder especially in naturally aspirated (NA) engines and creating an internal exhaust gas recirculation (EGR) responsible for some NOx reduction. All engines have a maximum allowable engine backpressure specified by manufacturer. An engine operated at excessive backpressure might invalidate its warranty (Chaudhari *et al.* 2015).

Measuring the exhaust backpressure

Exhaust backpressure is measured as the engine is operating under full rated load and speed conditions. It is measured through method either a water manometer or a gauge measuring inches of water may be used. The water manometer pressure measurement is shows in Figure-3. Many engine installations are already equipped with a fitting in the exhaust discharge for measuring backpressure. However, some of the manufacturer Nowadays, uses the mercury manometer in backpressure guage. It is generally decided by automotive engineers for every inch of Hg of backpressure (mercury pressure guage unit) approximately 1-2 horsepower (HP) is lost depending on the displacement of the engine, the combustion chamber design and etc (Pinelli & Bucci 2009).

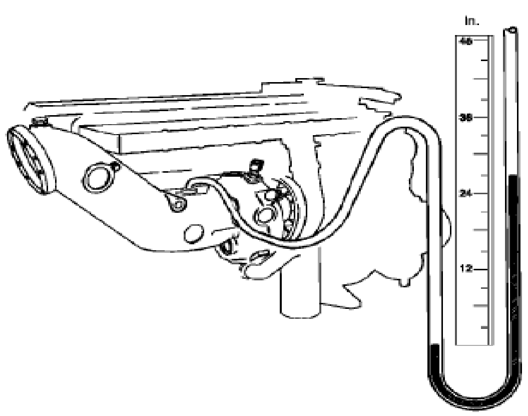

Figure-3. Water manometer (Pinelli & Bucci 2009).

Modification of silencer position and exhaust flow design

The exhaust system is designed to evacuate gases from the combustion chamber quickly and efficiently. The character of exhaust gases produced is not in a smooth stream but originate in pulses whereby the number of pulses is depending on number of outlet of the exhaust manifold which attached with gases extractor. The more pulses produced, the more continuous the exhaust flow. At the same time, backpressure phenomena will happen in the exhaust system which resistance to positive flow of the exhaust stream. Backpressure also influenced by several factor such as diameter of exhaust piping, length of pipe, number of bends in piping system, silencers, muffler, resonators and catalytic converters. In this study, the exhaust system initially has overall length of 11.5 meters and one bending pipe with the position of silencer is 3.0 meters from the exhaust manifold/header. However the exhaust system of the engine has been modified to new flow design and silencer arrangement which caused the major changes in exhaust piping dimension. The new exhaust system has 13.5 meters of total length with two bending pipes while the silencer is locating 10.0 meters from exhaust header.

The changes of the dimension and arrangement of exhaust system is definitely affecting the gases flow behaviour travelling the pipe as well as forming higher backpressure inside the piping in term of volume, velocity and pressure of the exhaust gases. These changes are influencing the performance of the internal combustion and engine efficiency as well. In the study, the reseach was focused on the flow of exhaust gases produced by Yanmar 4-stroke diesel generator engine with capability of 125 HP. The engine is located at Marine Engineering Workshop, Politeknik Ungku Omar. Nonetheless, the study is limited to analysis on the backpressure levels, dimension of exhaust system and silencer arrangement.

Working principle of CFD on exhaust gas flow

Study on effect of backpressure on exhaust system of four-stroke diesel generator due to exhaust flow design and silencer arrangement has been carried using computation fluid dynamic (CFD) method approach to analyse the simulation results which focused on the effects on the exhaust backpressure. The results from experimental test and cfd simulations will be utilised for data analysis and comparison. The summary of research works is simplified in a flow of integrated working procedure of CAD, CFD as well as FEM is demonstrates in Figure-4. The model of test setup would be passing air at fixed mass flow rate through the entire exhaust piping system including the silencer. The algorithm to generate the mesh is based on the geometrical discontinuity or “gap size” and it increases the number of cells in proximity of narrow channels, corners gaps, and etc. The code solves the Navier–Stokes equations through a Reynolds averaged approach and uses a finite volume method for the equation discretisation (Kesgin, 2005).

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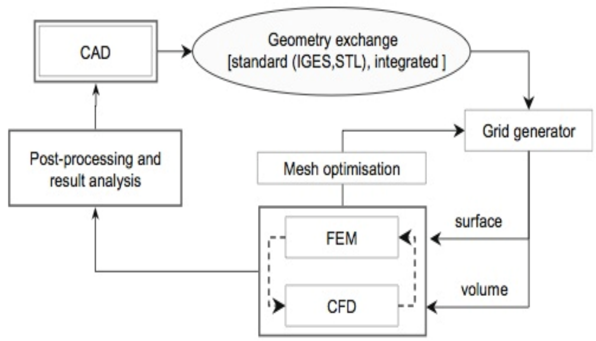

Figure-4. CAD/CFD/FEM integrated procedure (Pinelli & Bucci 2009).

Gas dynamics models have been use the mass, momentum and energy conservation equations for unsteady compressible flow in the exhaust and inlet pipe systems (Pinelli & Bucci 2009). The flow in a pipe of an engine exhaust and inlet system is treated as one dimensional problem. One dimensional means the pressures, temperatures and flow velocities obtained from the solution of the gas dynamic equations which represent mean values over the cross-section of the pipes as per following Figure-5.

$$\frac{\partial}{\partial t}\begin{pmatrix}\rho\\ \rho U\\ \rho u\end{pmatrix}+\frac{\partial}{\partial x}\begin{pmatrix}\rho U\\ \rho U^2+p\\ pU+\rho Uu\end{pmatrix}=\begin{pmatrix}-\rho U\frac{\mathrm{d}A}{\mathrm{d}x}\\ -\rho\frac{U^2}{A}\frac{\mathrm{d}A}{\mathrm{d}x}-\rho\frac{2\xi U|U|}{D}\\ -\frac{4h_c(T-T_w)}{D\rho}-\frac{1}{A}\frac{\mathrm{d}A}{\mathrm{d}x}\left(\frac{1}{2}\rho U^3+\frac{\gamma}{\gamma-1}Up\right)\end{pmatrix}$$

Figure-5. The conservation equations for mass, momentum and energy (Pinelli & Bucci 2009).

where q is the gas density, t is time, U is the gas velocity, u is the specific internal energy of the gas, p is the pressure, A is the flow area, x is the coordinate, n is the friction coefficient, D is the equivalent diameter of the flow area, h_c is the convective heat transfer coefficient, T is the gas temperature, T_w is the wall temperature and c is the ratio of specific heats.

The design and properties of silencer is needed to run the simulation of the project. One of properties is air flow pressure. When steady air flow passes through mufflers, there will have steady pressure drop which is related to flow and geometry of air passages (Lota *et al.* 2014). Pressure drop in an exhaust silencer and muffler plays an important role for the design and development of these components. Assumption and boundary conditions:

1) Flow is considered to be steady
2) Air is considered as the fluid for computations
3) Flow considered as Turbulent (K-ε Model)
4) Inlet considered as Mass flow boundary condition in 320Kg/hr
5) Inlet Temperature of fluid in 520 °C
6) Outlet considered as pressure outlet opened to atmosphere.

Generally an exhaust muffler and silencer should satisfy some basic requirements such as adequate insertion loss, low backpressure, ideal sizing which could affect the cost and accommodation and the last one could be the durability to withstand rough conditions and extremely high temperatures. Hence some design considerations have to be taken in order to come up with an optimum design. The parameters that govern the performance of the muffler or silencer are the chamber design restrictions of the flow of the exhaust gases and the material of the muffler or silincer itself (Kore, Aman, & Direbsa, 2011; Mohiuddin, Ideres, & Hashim, 2005).

The relationship between the noise and the backpressure is inversely proportional; lowering the noise level at the tip will result in high backpressure. However, this relationship is undesirable as the requirement is to have a quiet muffler/silencer with a small backpressure. The higher backpressure created by the exhaust system, the less net power available on the crankshaft and the more specific fuel consumption (SFC) with efficiency's drop. The amount of power loss depends on many factors, but a good rule-of-thumb is that one inch (25.4 mm) of mercury backpressure causes approximately 1.0% loss of maximum engine power (Middelberg *et al.* 2003).

METHODOLOGY AND PROCEDURE

In this study, we use 4-Stroke Diesel Engine that located at Marine Engineering Workshop, Politeknik Ungku Omar. The design of the exhaust piping from engine outlet to the silencer until the end tip was drawn using CAD software. The design of the exhaust piping has been changed due to re-arrangement of older diesel generator engines fitted area to allow new diesel generator engines installed in the same workshop. The old piping design of exhaust diesel engine before modification in the workshop is depicts in Figure-6.

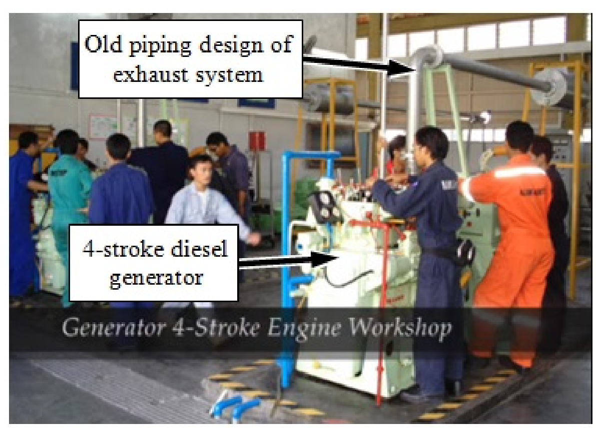

Figure-6. 4-stroke diesel generator engine located at marine engineering workshop, PUO.

The silencer attached at 2 meters from the engine and the exhaust piping bended upward in order to ensure the safety of people and satisfactions in the working area during practical session. The engine was tested after the installation was completed. The data was recorded in order to compare the performance of the engine and will be used

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as a reference. Especially when the modification of the exhaust system and maintenance of the engine were completely done then the performance of the engine must be tested once again. In this study, the modification of the exhaust piping system and silencer placement was already completed for the reason of installation new engine as state before. Therefore, the tests need to be carried out by using CFD method approach to determine its theoretical performance before proceed to the experimental method. The simulation is focused on exhaust backpressure of the whole exhaust piping system and an engineering CFD package application is used to carry out the simulation.

Figure-7 and Figure-8 shows the drawing for old design and new design after modification. The drawing are completed using CAD software and has been inspected in order to ensure it suit and compatible working in the selected engineering CFD package application for running simulations based on fluid flow and pressure analysis. The CFD software allows the user to create a mesh surface and define the boundary conditions of the required developed model, which will be read and analysed.

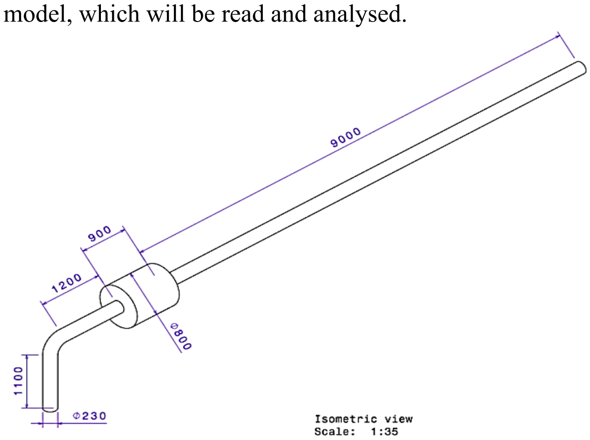

Figure-7. Old design of exhaust piping for diesel generator engine.

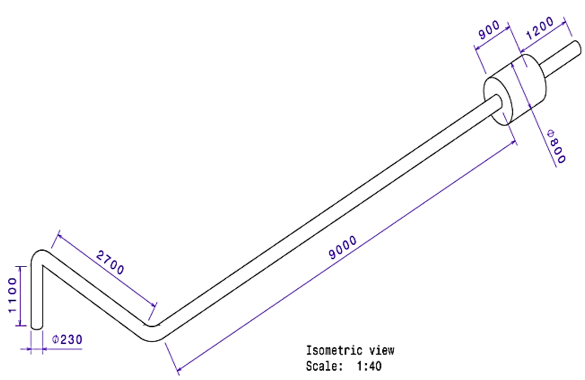

Figure-8. New design of the exhaust piping for diesel generator engine using CAD software.

The inlet is defined as the velocity-inlet boundary and the outlet is defined as the pressure-outlet boundary. The file was gather and arrange neatly in a folder and been saved and yet the analysis was carried out using the output results of the simulation test. The input parameters used in the simulation are as follows according to Figure-8:

1) Inlet pipe length: 0.23 m
2) Outlet pipe length: 0.23 m
3) Expansion chamber length: 0.9 m
4) Expansion chamber diameter: 0.8 m
5) Length pipe before 1st bend for old design: 1.1 m
6) Length of pipe after 1st bend to outlet for old design: 11.1 m
7) Length pipe before 1st bend for new design: 1.1 m
8) Length pipe after 1st bend to 2nd bend for new design: 2.7 m
9) Length pipe after 2nd bend to outlet for new design: 11.1 m

Other input parameters are the air flow temperature and the air pressure.

The flow chart of overall research works which begin with concept review and ended with discussion on CFD experimentation results is illustrates in Figure-9.

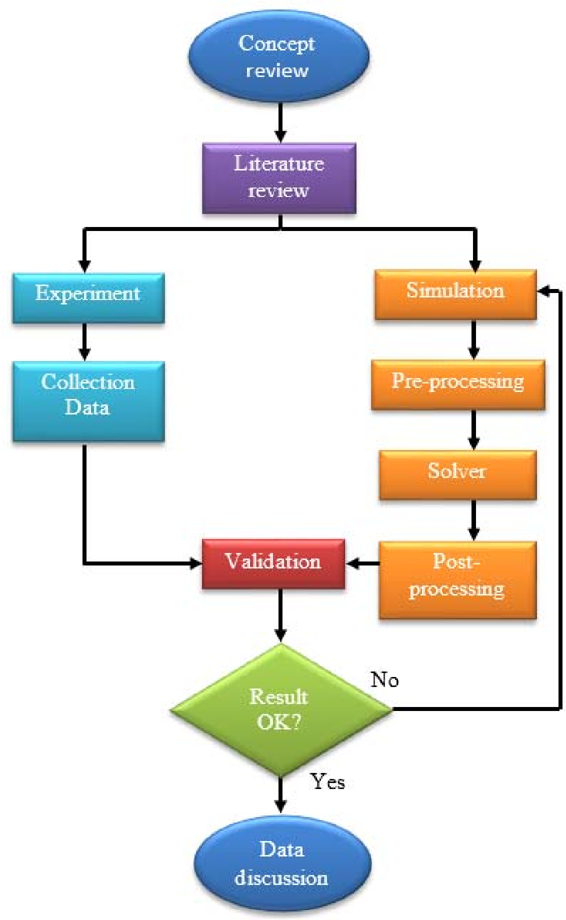

Figure-9. Flow chart of research methodology.

CFD RESULTS ANALYSIS AND DISCUSSION

The result of experiment which is through engine operations was compared to the simulation result run by an engineering CFD application to validate the parameter used in the simulation. The input parameter used is pressure and temperature at both inlet and outlet of the exhaust pipe. After validate the parameters, the simulation for the new design of exhaust pipe would be run by the

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same engineering CFD software application. The result of both designs (older and new) was compared to find out which is the best exhaust piping design that optimise the engine performance, efficiency and resulting in better fuel consumption. The result also shows either the silencer position in the exhaust pipe system is majorly effect the performance or not in terms of its backpressure. The comparison results are focused mainly on the pressure from pipe inlet (engine outlet), whole exhaust flow piping (wall) until the outlet of the pipe (boundry between exhaust gases inside the piping and atmosphere). The temperature and velocity also compared between both designs.

The complete drawing of model is saved in iges or IGS format to suit with the engineering CFD software application. In the engineering CFD software application used, an analysis system of Fluid Flow (CFX) was used. After complete meshing the design of exhaust piping system, the parameters was setup before running the solution and getting the result. During results generation, the graph of momentum and mass can be observed either it meet the convergence or not to monitor and ensure that the test is valid and running properly. The graph of momentum and mass over the accumulated time step of simulations which generated during the solution process in this study is illustrates in the following Figure-10.

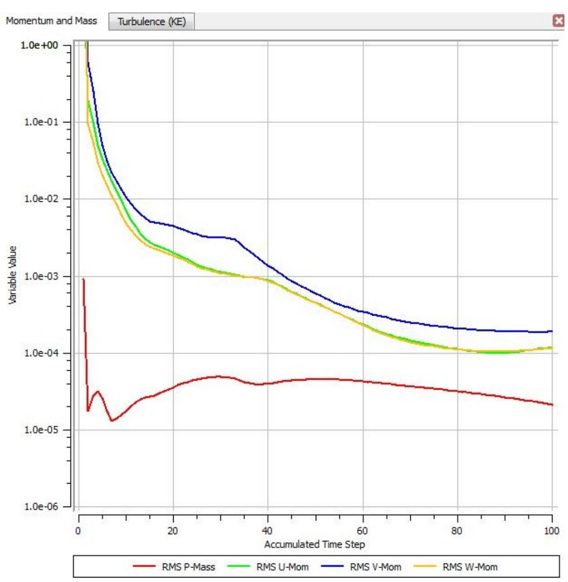

Figure-10. Graph of mass and momentum generated during solution process of CFD.

Pressure contour

Figure-11 and Figure-12 shows the results of simulation in terms of pressure contour for older and new silencer and exhaust piping flow design. By referring to Figure-11, the result for old design where the pressure at the outlet ≈1.021 x 10^5 Pa is less than pressure at inlet which is ≈1.963 x 10^5 Pa. While from Figure-12 that demonstrates the result for new exhaust system design has the pressure at outlet ≈9.405 x 10^4 Pa which is less than pressure at inlet ≈1.985 x 10^5 Pa. In conjunction, the variants of average pressure along the exhaust piping between old and new exhaust system is 2%. The results of simulation for both exhaust flow design indicates that the pressure was gradually decreasing corresponding to the overall length of the exhaust piping. As we know, when the speed of fluids (exhaust gases) increased, the pressure will decreased while the pressure will increased if the speed of fluids decreased. Based on these simulation results, it can be concluded that the performance of the exhaust piping system for new design not so much affecting the changes in pressure particularly exhaust backpressure.

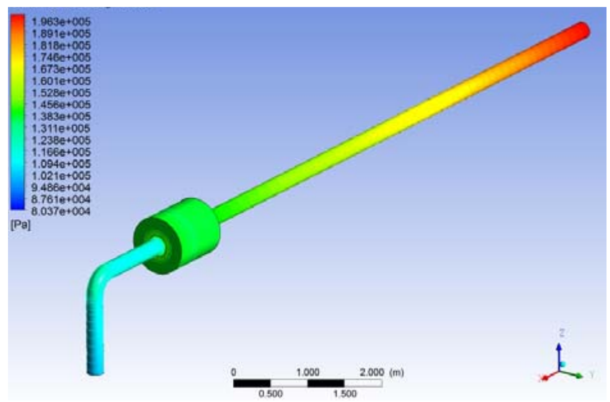

Figure-11. Pressure contours of static pressure for old silencer and exhaust flow design.

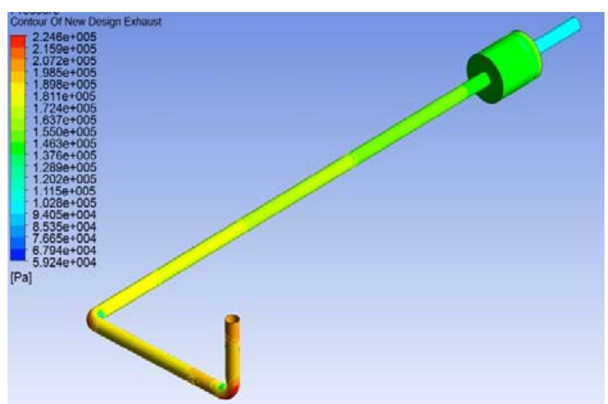

Figure-12. Pressure contours of static pressure for new silencer and exhaust flow design.

The backpressure occurs inside the piping system when the pressure at inlet increased and push back part of the fluid (gases) flowing through the pipe to the outlet. The backpressure occurs in the exhaust pipe close to the inlet of pipe helps in optimising the performance of the 4-stroke engine. In addition, it can be observed from both figures that pressure was slightly increased when the exhaust gases reaches and hits the bending area/elbow of the exhaust pipe as well as at the end edge of the silencer. Hence, these results are remarks the sign of backpressure development onto the system.

Velocity contour

The flow of fluid in ducts and pipes will experience the changes in pressure and velocity. The simulation has been carried out under engine speed of 1500 rpm and inlet pressure of 4 bar. The pressure of fluid decreases as the fluid speed increases and vice versa. The air at inlet and outlet pipe has a greater velocity compared to the air flow in the expansion chamber or silencer which can be observed from the simulation results. The colour contour indicates the velocity of air moving through in and out of the exhaust piping system and the velocity of the air in the silencer as well. Figure-13 and Figure-14 demonstrates the variation of velocity of exhaust gases flow through the exhaust system from inlet pipe to the outlet pipe for both old and new new silencer and exhaust flow design.

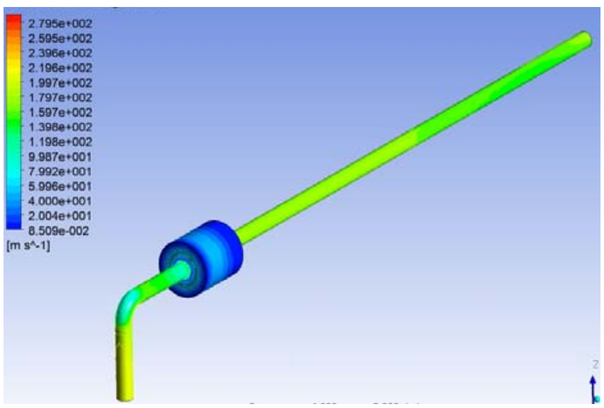

Figure-13. Velocity contours for exhaust gases passing through the old silencer and exhaust flow design.

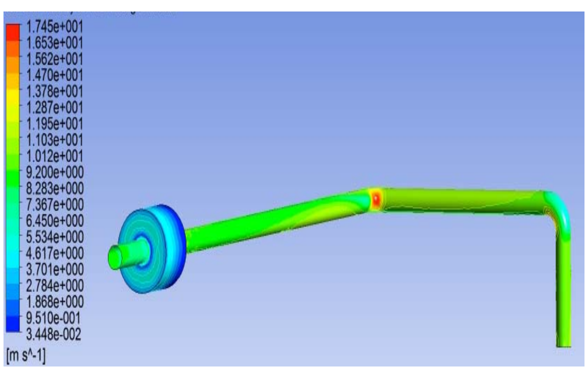

Figure-14. Velocity contours for exhaust gases passing through the new silencer and exhaust flow design.

From the results of simulation on velocity contour, the investigation has found that there is a contrary relationship between fluids pressure and velocity which conforms the Bernoulli's principle. For both old and new design of exhaust system, mainly around the silencer region there is the indication of variation velocity loses due to the sudden expansion of fluid volume when travelling under speed of 1500 rpm. These occurrence were happened due to backpressure that is generated within the silencer chamber whereby the molecule of fluids moving actively and burst yet forming vortex. The maximum drops in velocity in the expansion silencer of old and new exhaust piping system design are ≈8.509 x 10^{-2} m/s and ≈3.448 x 10^{-2} m/s respectively which indicates about 84.7% drops. From these simulation results, for both old and new exhaust system design specifically at the bending region, there is an indication of velocity loss when reach the first bending region of ≈7.992 m/s and ≈4.617 m/s for old and new exhaust piping design respectively. However, by referring to Figure-14, the velocity of fluid flow was then increased extremely to ≈1.745 x 10^{1} m/s when reach the second bending of the pipe flow. Nevertheless, form the simulation results, it can be observed that the minimum or the lowest velocity of fluids represent by the new design of exhaust system. On the other hands, the velocity loss of the silencer indicates the noise cancellation in the expansion silencer which signify a good performance of the engine output power since the majority of the transmission loss value lies within the range of 20 dB to 43 dB (Middelberg *et al.* 2003).

Pressure streamlines

The pressure streamline indicates the pressure dissemination along the exhaust piping system as shows in Figure-15 and Figure-16. If at any one of the cross sectional area of the pipe was examined, the different magnitude of pressure from one point to others will be found. From the simulation results, the streamlines of pressure distributed along the exhaust system for old silencer and exhaust flow design is illustrates in Figure-15. It was recorded that for the old design, the inlet pressures streamlines to be relatively higher at around the range of ≈3.799 x 10^5 kg/m^{2}s^2 to 5.698 x 10^5 kg/m^{2}s^2 compared to outlet pressure streamlines. Once the exhaust gases flow and reach the silencer chamber, the simulation results streamlines pressure signifies that the pressure was changing it behaviour where it burst and filling up almost the space inside the silencer. In this silencer chamber, the pressure stat to decrease immediately before leave out the chamber. As the fluids passing by the expansion silencer, the pressure streamlines are remarkable has somewhat uniform values of ≈4.071 x 10^1 kg/m^{2}s^2. That is means the pressure was decreasing gradually until achieve the atmospheric pressure after leaving the exhaust system. From this finding, the backpressure occurred at the inlet pipe and part of them occurred in the silencer due to the high pressure at the inlet tend to push back the fluids (exhaust gases) during flowing through the pipe to the outlet part or pipe tip.

In other hands, the simulation results of pressure streamlines distributed along the exhaust system for new silencer and exhaust flow design is shows in Figure-16.

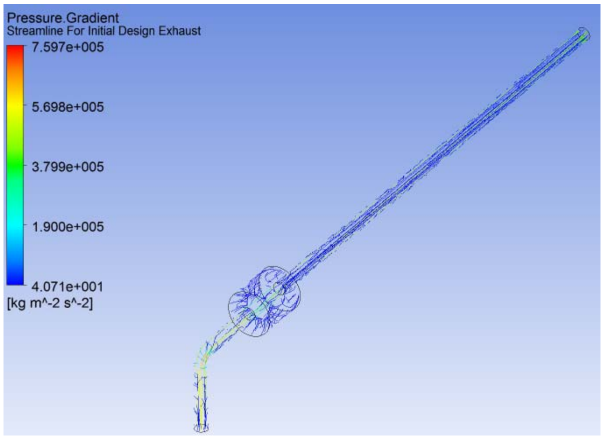

Figure-15. Streamlines of pressure along the exhaust system for old silencer and exhaust flow design.

From Figure-16, it can be observed that the streamlines of pressure at inlet and outlet pressure is relatively uniform at about ≈1.0576 x 10^6 kg/m^{2}s^2. However, the lower pressure occurs once the fluids reach and passing through the silencer chamber because there is a larger in diameter and space of the silencer, where the pressure is distributed to all space of the expansion silencer. The magnitude of streamlines of pressure within the silencer chamber when the exhaust gases travelling through it are around the range of ≈7.141 x 10^1 kg/m^{2}s^2 to ≈5.288 x 10^5 kg/m^{2}s^2. The old exhaust piping system design demonstrates a higher initial pressure at the inlet region at around ≈3.799 x 10^5 kg/m^{2}s^2, but there is an obvious growth in pressure streamlines distributions for the new exhaust piping system design at value around ≈1.057 x 10^6 kg/m^{2}s^2 where the difference is 94.7%. From this result, it was remarked the disseminations of pressures are about uniform pressures acts along the piping system except for the silencer, whilst backpressure occurred inside the silencer due to higher pressure created by the movement of gases inside pipeline. This backpressure was slightly higher than that occurred to the old exhaust system and for sure affecting the performance of diesel generator engine.

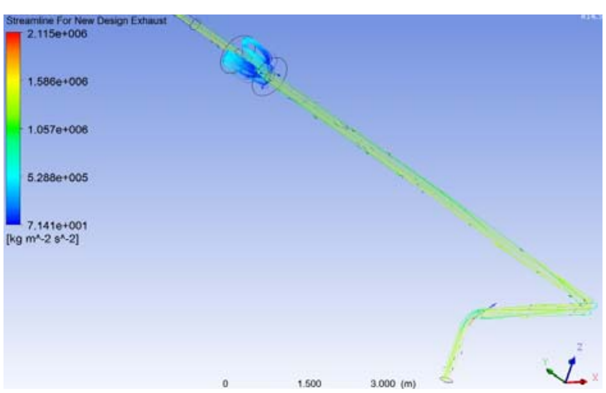

Figure-16. Streamlines of pressure along the exhaust system for new silencer and exhaust flow design.

Velocity streamlines

The velocity streamlines indicates the flows of exhaust gases in velocity behaviour or the changes of fluids displacement over the time taken for the changes done. For the old flow design of exhaust piping system as shown in Figure-17, it is dictates that the velocity of gases travelling the pipe very fast starting from inlet until reach the silencer or expansion chamber with velocity around ≈2.089 x 10^2 m/s. However the velocity is then reduce immediately about 44.7% and maintain at range of ≈1.083 x 10^2 m/s to ≈1.586 x 10^2 m/s when approacing closer to the silencer as well as after leaving the silencer until the exhaust tip. In the silencer chamber, the velocity streamlines shows that the gases is not just pass through the silencer but it suddenly change it flows to circulation motions and perhaps formation of vortex which causing the velocity reduces more than 100% before leaving the silencer. During this velocity drops, which is begin at bend pipe followed by the occurrence of circulation as well as vortex formation inside the silencer, the exhaust backpressure definitely generated due to the changing in direction and dimension of fluids flow particularly in silencer diameter and volume of flowing gases. The streamlines of velocity is then increase again once leave the silencer through velocity about ≈1.586 x 10^2 m/s and bit by bit decrease until the value of velocity around ≈1.083 x 10^2 m/s until the gases reach the exhaust outlet and escape to atmosphere.

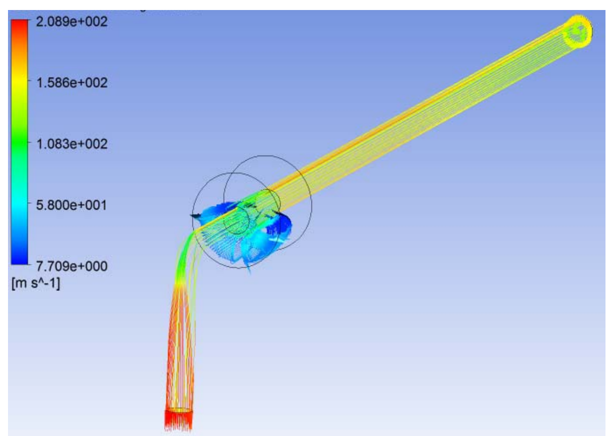

Figure-17. Velocity streamlines of gases flowing throughout the old exhaust piping system.

As for the new silencer arrangement and new exhaust flow design as demonstrates in Figure-18, the enormous different compared to old exhaust system design that remarked is the characteristic of velocity streamlines start from inlet pipe promotes about uniform and maintain velocity level of flow gases which travelling at range of ≈8.731 m/s to ≈1.309 x 10^1 m/s until reached the outlet of exhaust system. Despite that facts, once the exhaust gases entering the silencer chamber, the velocity decreased more than double i.e. >100% at the upper range velocity ≈1.294 x 10^1 m/s to ≈4.372 m/s and the flow characteristic is immediately changed to circulation type of motions and

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probably generates vortex behaviour of the fluids flow. As the velocity decreased, the pressure will increase which fulfil the Bernoulli's principle, which possibly directed to the development of exhaust backpressure on the overall exhaust piping system. Nevertheless, it can be dictates from Figure-18 the streamlines of velocity were then increased around ≈8.731 m/s to ≈1.309 x 10^1 m/s again once leaving the expansion silencer until reach end of outlet and emit to the outside air.

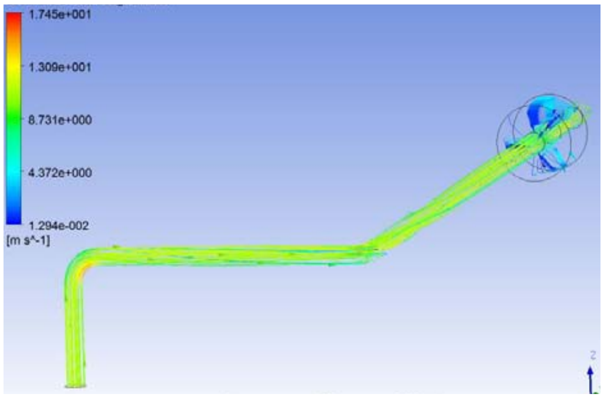

Figure-18. Velocity streamlines of gases flowing throughout the new exhaust piping system.

Based on these two types of exhaust system design, the similar flow conditions happened in the silencer or expansion chamber with dissimilar magnitude of velocity. The velocity of gases at piping between the silencer were higher than velocity of gases inside the silencer chamber (which means of some velocity dropped) associated with changing of flow behaviours to generate some pressure which also known as backpressure. Aside, some amount of this backpressure is useful to be kept and maintained within the exhaust piping system or certain amount of backpressure remains in the exhaust piping system to let exhaust gases may flow continuously, consistently and efficiently from exhaust manifold at the engine until leave the exhaust pipe to ensure the efficiency and yielding an optimum performance through either higher torque at lower speed or lower torque at higher speed of the diesel generator engine.

CONCLUSIONS

The study of CFD analysis on the effects of exhaust backpressure generated in exhaust system of 4-stroke marine diesel generator engine before and after modification of silencer position and exhaust flow design has been accomplished. The conclusions were lay emphasis on the effects of backpressure occurrence in the entire system of exhaust piping during generator operation under engine speed of 1500 rpm. The old silencer and exhaust flow design resulting a gradual decrement of velocity of gases from inlet to atmosphere with extreme reductions at silencer region, whilst for new exhaust flow system bring about a uniform velocity of gases flowing from inlet to atmosphere with similar manner during crossing the silencer. In other hands, the old silencer and exhaust flow design experiencing pressure increment from inlet to atmosphere with inconsistent pressure behaviour inside the silencer which is an indication of backpressure formation, while a contrary effects by new exhaust system which experienced the pressure reduction from inlet until reached the outlet with erratic pressure behaviour at the silencer region as the significant of backpressure development. In conjunction, the maximum and average pressure generated by the new exhaust piping design is higher than old design with relative percentage different of 94.7% where an indicator of backpressure progression. In overall, the magnitude of backpressure disseminated over the entire new exhaust system design is higher than that of old design. This study was confirming that the changes of overall length of exhaust piping, numbers of bend pipes/elbow and silencer of new exhaust system is directly affecting the rise of backpressure and a tad drop in efficiency of power generation.

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