Mindanao Journal of Science and Technology Vol.16 (2018) 211-230

Effects of Viscosity and Heat Transfer on Developed Marine Fuel Preheating System Utilizing Diesel Engine Exhaust

Ralph Martin L. Castellano[1*], Antonio-Abdu Sami M. Magomnang[1] and Eliseo P. Villanueva[2]

[1]College of Engineering and Architecture
University of Science and Technology of Southern Philippines – Cagayan de Oro
Cagayan de Oro City, 9000 Philippines
[*]*lalarpengr@gmail.com*

[2]College of Engineering
Mindanao State University – Iligan Institute of Technology
Iligan City, 9200 Philippines

Date received: August 1, 2018
Revision accepted: October 15, 2018

Abstract

Diesel engines in maritime applications exert heat energy from combustion gases. The main engines are the prime movers of ships and vessels; used marine fuel oil serves as working substance while the auxiliary diesel engine provides mechanical energy to the electric generator through the combustion of diesel fuel. The marine fuel oil preheating system is a contributor for energy consumption and diesel fuel consumption of auxiliary engines. Research on waste heat recovery from exhaust gases led to an alternative source of heat which may be applied to marine fuel oil as it enters the electrical operated pre-heater and purifier. The purpose of this study is to determine the heat transfer equations for fluid heat exchanger, heat transfer conduction and convection through pipe. The mathematical equation derivation resulted specifications, size and dimensions of a serpentine coil, conveying pipe and baffle plate of the heat exchanger assembly. This was done by fabricating a serpentine copper coil tube due to the higher thermal conductivity of copper compared to other tubing materials. The conveying pipe and baffles were made from 1.2 mm steel sheet because of its durability and availability in the market. Results of the conducted test and simulation have shown that 92% heat was gained from the aimed temperature. Heat transfer units were also enough to heat marine fuel oil. A highly viscous fluid ranges from 150 to 190 centistokes at normal temperature reduced its viscosity to 119 centistokes at 57°C. This is the target temperature to feed the fluid through a purifier.

Keywords*:* diesel engine, exhaust gas, heat exchanger, serpentine, waste heat

---

1. Introduction

Diesel engines in marine industry are the prime mover and power producer of ships and vessels (Deshpande and Bux, 2015). The main engines are tasked to be the prime mover of the vessel and the auxiliary engines are used to drive the generators or alternators which are the vessel's primary source of electrical power. The crankshaft of the main engine produces power which is coupled into a propeller shaft that pushes the vessel forward. The auxiliary engine is then joined into a shaft which drives the electrical generator to produce electrical power for the entire ship (Nitonye, 2018). Diesel engine converts chemical energy of fuel into mechanical energy through the process of burning the liquid fuel mixed with air to create hot gases and products of combustion that are released in the exhaust.

Thermal energy from unburned gases is released in the atmosphere. From the engine room, an exhaust pipe is constructed to convey the exhaust gases from the diesel engine to the naval chimney. The working substance of these engines is automotive diesel oil (ADO) or commonly known as diesel. Auxiliary engines are power generating units for vessel's electricity on board and utilize diesel as fuel. This engine has an average speed of 1,000-1,800 Rpm. Main engine manufacturers are low speed type with average speed of 200 – 1,000 rpm and may be fueled with diesel. To save on cost, the industrial fuel oil (IFO) or so called marine fuel oil is used. IFO is a low-grade fuel, highly viscous and its sulfur content ranges from 2% to 3 % (Chevron Marine Fuel Oils, 2018).

Marine fuel is injected in the combustion chamber of the diesel engine. Purification and filtration process is applied to ensure cleanliness and to separate impurities from the fuel. The fuel oil should be preheated to reduce its viscosity and avoid clogging in the supply line of the purifier. The preheating equipment is electrically operated and thus consumes energy from the generator.

The marine fuel needs to be purified before feeding to the diesel engine fuel injector to ensure fuel cleanliness, filter the sediments in the fuel to avoid pipe clogging; however, purification could be difficult when fuel oil is at normal and ambient temperature. A pre-heater is installed before the purifier. This equipment reduces the fuel oil viscosity and allow the fluid to flow easily to the purifier.

Recent studies on effect of heated fluid inside the tube of a serpentine heat exchanger directed this research to determine the temperature and mass flow rate effect. The study on numerical analysis and flow network evaluated the number of transferred units (NTU) in every heat generation using heat as dependent variable (Pagare *et al.*, 2016). Numerical analysis of parallel flow heat exchanger showing comparative results for number of transferred units (NTU) versus log mean temperature difference (LMTD) is the basis on comparing the NTU and LMTD of the system.

The objective of this study is to preheat marine fuel oil using alternative source of energy. The study is limited to the evaluation of the effect of mass flow rate with corresponding temperature. The effectiveness of the heat exchanger was investigated and compared to every heat added on the system. The log mean temperature difference (LMTD) of the copper material was compared to the number of transferred units (NTU) to check the capacity of material to transfer heat on the fluid (Hossain and Bari 2011). Software simulation was conducted to visualize the temperature distribution and flow trajectory of the system and to determine which part of the designed heat exchanger has high heat concentration.

2. Methodology

Inside the engine room, three auxiliary engines coupled to an electric generator were supplied with diesel fuel. These generators were wired in parallel to allow any energy variations of electrical load on board. The marine fuel oil flowed through a pre-heater before purification began. The electric pre-heater consumed energy at 5 kilowatts. This was to reduce the marine fuel oil's viscosity and to allow smooth flow in purifier pipes. After purification, the marine fuel oil flowed to the main engine where it was used as fuel. The encircled component was the designed serpentine heat exchanger that passed the exhaust gas coming out from the main engine as shown in Figure 1.

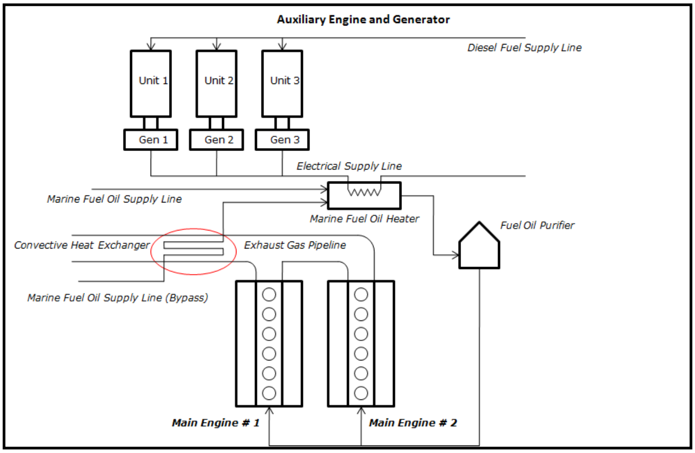

Figure 1. Process flow and schematic diagram of heat exchange setup inside the passenger type M/V Trans Asia 9 & 3

2.1 Preheating and Purifying Equipment

The engine room is part of the vessel and the compartment where machineries and power generating units are located. The pre-heater in the purification equipment is focused in this study. Figure 2 shows the equipment inside a vessel's engine room.

Figure 2. Marine fuel preheating and purification system

The vessel's main engine is the source of the exhaust gas in which the products of combustion from the main engine is conveyed to naval chimney. This is also the location where the designed heat exchanger was installed.

The vessel's engine room was drafted in software to visualize the isometric view inside the engine room shown in Figure 3 and the heat exchanger assembly shown in Figure 4.

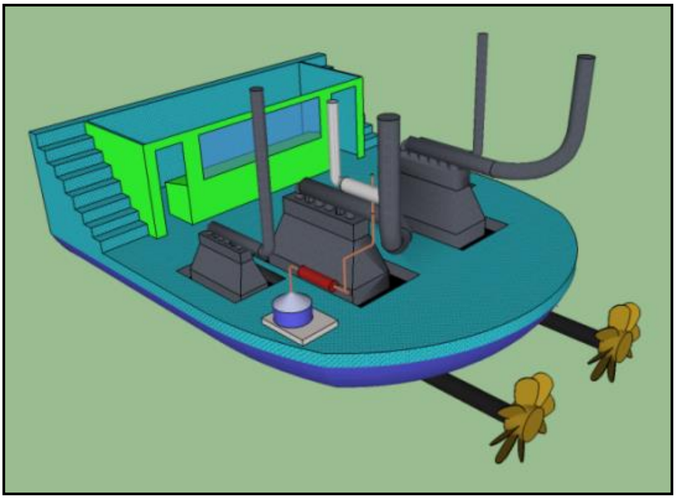

Figure 3. Isometric view of engine room

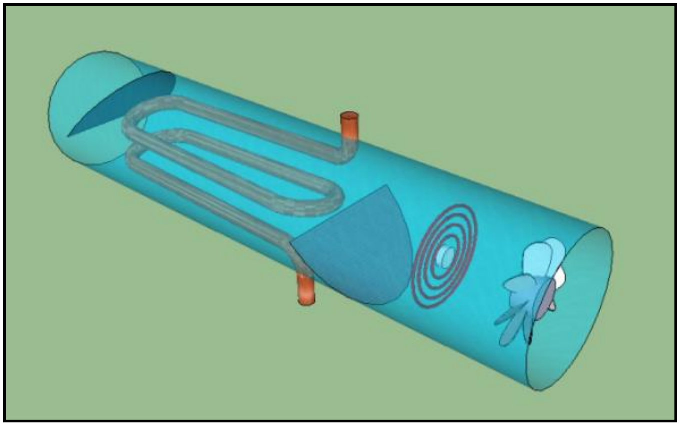

Figure 4. System setup schematic and process flow diagram

The experiment set-up was equiped with fan, coil heater, serpentine tube and heater. The study evaluated the heat transfer of the heat exchanger using two heating medium namely air and exhaust gas to determine the capability of actual heating. Table 1 shows the actual fan properties and capabilities available in the market.

Table 1. Actual fan properties for the experiment setup

Fan Specifications	
Model :	FP-10108EX
Capacity:	Q = 6 M^3/min
Power :	32 W
Speed:	2,800 Rpm
Air Density	1.225 Kg/m3
Cp Air	1.826 Kj/Kg – k

2.2 Calculating the Heat Exchanger Heating Capacity

The heat exchanger capacity using the specific heat formula based from the mass flow rate of the substance, specific heat of the substance and the change in temperature is found in equation 1.

$$Q_{air} = mC_p(t_2\text{-}t_1), \text{ (air as heating medium)} \tag{1}$$

This is the heating capability of convective air necessary to heat the substance. The heat capacity of exhaust gas in equation for specific heat formula was obtained in equation 2.

$$Q_{Exhaust\ Gas} = mC_p(t_2\text{-}t_1), \text{ (exhaust gas heating)} \tag{2}$$

Theoretically, the heat capacity of exhaust gas is directly proportional to its constant specific heat. This specific heat is higher than convective air and to ensure that the design is safe from the aimed heat. To determine the heat capacity of the marine fuel oil, the study used the specific heat formula as shown in equation 3.

$$Q = mC_p(T_2\text{-}T_1) \tag{3}$$

The heat required to heat the fuel oil showed to be lesser than the heating capacity of both exhaust gas and air.

2.3 Setup Calculations for the Convective Heat Transfer through Pipe

For the heat transfer of the material, the study calculated the thermal conductivity and overall heat transfer to ensure the capacity to heat the fuel oil inside the tube. The heat transfer formula for convection for outer radius is shown in equation 4. Transforming this into logarithmic formula for radius difference is shown in equation 5. The heat transfer formula for outer layer where heat transfer is outside the tube was shown in equation 6.

$$Q= h_o 2wr_o L(T_h\text{-}T_0) \tag{4}$$

$$Q = \frac{K}{log\left(\frac{r_o}{r_i}\right)} 2wL(T_h\text{-}T_0) \tag{5}$$

$$Q= h_i 2wr_i L(T_i\text{-}T_c) \tag{6}$$

The heat required to heat the fuel oil inside the pipe at ¾-inch schedule 40 pipe since it is the only copper tubing diameter available in the market. The air heating capacity is lower than both. The surface area heat transfer for heat exchanger was also obtained using equation 7.

$$Q = \frac{T_2 - T_1}{\frac{1}{\pi d_i h_{i\,(Fuel\ Oil)} L} + \frac{\ln(^{do}/_{di})}{2\pi KL} + \frac{1}{\pi d_o h_{i\,(Exhaust\ Gas)} L}} \tag{7}$$

After the heat transfer through pipes was obtained, the study determined the pressure difference in pipes using the pipe flow calculation formula in equation 8. The exhaust gas flow for the pressure difference of the exhaust pipe (Donaldson, 2018).

$$Exhaust\ (CFM) = \frac{\text{Exhaust Temp+460}}{540}\text{ X (Intake)} \tag{8}$$

The exhaust gas flow rate is at 6 m^3/s. This is the exhaust gas capacity required to compute the velocity. Taking the velocity of the exhaust gas, the study has the cross-section area of the pipe shown in equation 9 and the velocity; hence, values are substituted.

$$Q = AV \tag{9}$$

Solving for the pressure drop from the main engine's operating pressure, 13.5 kPa is the standard back pressure of the engine, with a constant k = 1.41 and gravity where g = 9.81 m/s^2 from the equation 10 (Potter, 1959).

$$V = \sqrt{\frac{2gkRT}{k-1}\left[1-\left(\frac{p^2}{p^1}\right)^{\frac{k-1}{k}}\right]} \tag{10}$$

2.4 Experimental Setup

The serpentine copper tubing was fabricated with braze welding, as shown in Figure 5. This tubing is where the fuel oil passes through. The inlet of the tubing is at the ambient temperature while the exit would reach the target 60°C. Copper was used in this study due to its high thermal conductivity, and sustainability.

Figure 5. Fabrication of serpentine copper tubing

The convective pipe was made of 1.2 mm thick steel sheet. This sheet was rolled, bended and fabricated into rivets as shown in Figure 6. The baffles were created based on the half of the cross section area.

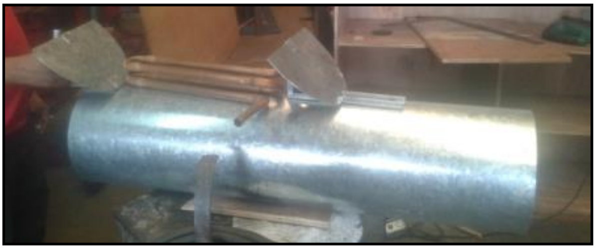

Figure 6. Fabricated heat exchanger assembly, baffles, serpentine coil housing

2.5 Testing and Data Gathering

Testing was conducted based on the parameters needed – the manual recording of fuel oil flow velocity, inlet and outlet temperatures and different fan speeds. The test used high speed fan, medium speed fan and low speed fan. Measuring air pressure is shown in Figures 7 to 9.

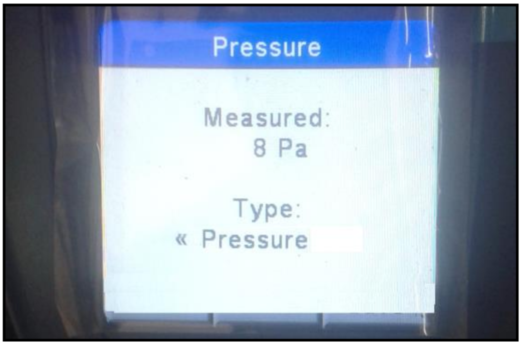

Figure 7. Measuring air pressure

Figure 8. Complete setup with fan attached

Figure 9. Heat exchanger assembly

3. Results and Discussion

3.1 Effects of Varying Temperature and Mass Flow Rate

The test was conducted using three levels of fan speed – low, medium and high. The resulting actual temperature was taken based on these varying levels. The three levels of heating coil temperature were also high, medium and low. Results showed the highest level of mass flow rate of air inlet temperature at low fan speed and high heating coil temperature as illustrated in Figure 10 below. The reduction of fan speed resulted an increase in temperature.

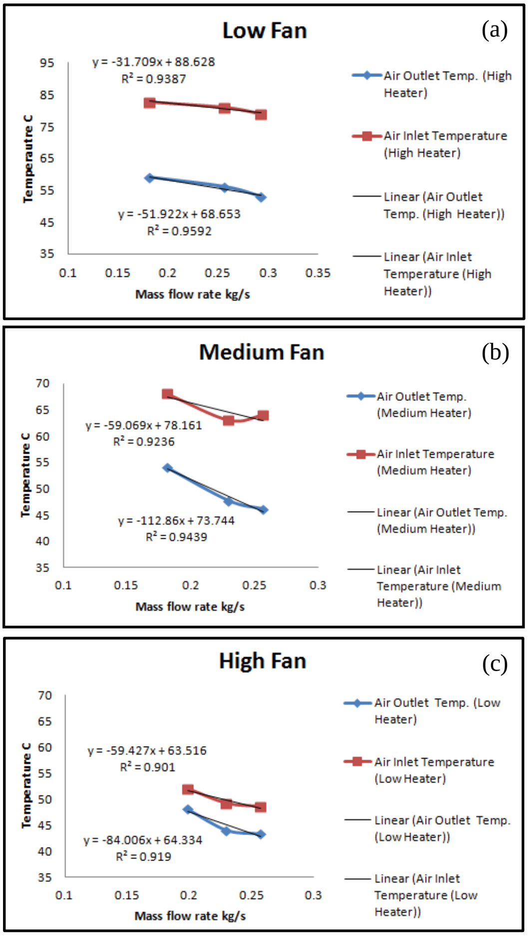

Figure 10. Relation between fuel oil mass flow rate with respect to fan speed and temperature. a) Lower speed of fan in high effects of heating; b) medium speed of fan in medium effects of heating; and c) high speed of fan in low effects of heating

Based on Figure 10, the mass flow rate is inversely proportional to its temperature and the heat generating equation for heat exchangers in which the heat generated mass flow rates and temperature difference are related.

$$Q = mC_p(t_2\text{-}t_1) \tag{11}$$

where:

Q = Heat capacity
m = Mass flow rate
C_p = Specific heat
t_2 = Outlet temperature
t_1 = Inlet temperature

This focused on the flow behavior of our marine fuel oil. The data was used with respect to the data gathered on the study on performance of serpentine heat exchanger and effect of heat with the fluid inside the tube (San *et al.*, 2009). This focused on the heating of marine fuel inside the serpentine tube.

3.2 Heat Generation of Heater and Transferred Heat

Comparison of the heat generation released from 1,800 kW capacity coil heater and the heat transfer effectivity showed that heat transfer effectivity of the number of transferred units increases in the same direction with the increase in heat generation as shown in equation 12. As heat was added to the serpentine coil, more heat was also released from the material to the fluid to be heated. The data shown in Figure 11, which was based in the study on development of the numerical analysis model of a flow network for a plate heat exchanger (Yoon and Jeong, 2017), illustrated that the heat generation is the dependent variable, equation 12 where NTU is the number of transferred units and U is the heat transfer coefficient.

$$NTU = \frac{U(\text{pipe Surface Area})}{\text{Capacity Ratio}} \tag{12}$$

where:

NTU = Number of transferred units
U = Heat transfer coefficient

This result focused on marine fuel heating through a serpentine coil and exhaust gas as source which is an innovative study for a plate exchanger and serpentine coil (Simon and Alshare, 2009).

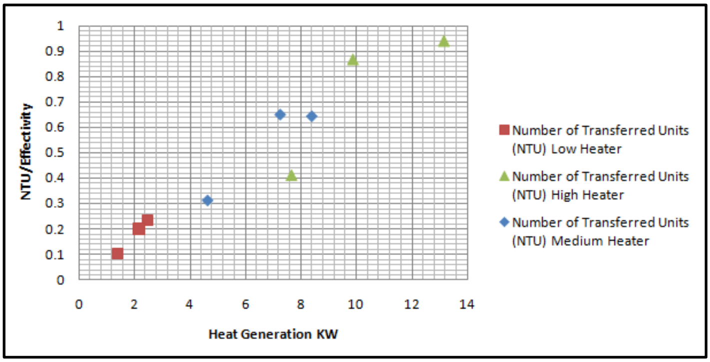

Figure 11. Effectivity of heat transfer per heat generation

3.3 Log Mean Temperature Difference and Number of Transferred Units

The LMTD is shown in equation 13 and the number of transferred units NTU is shown in equation 14. LMTD is the temperature relationship between two working substances, inlet and outlet temperature of fuel oil and air as heating medium (Edwards, 2008). This is also indicator of how fluids exchanged heat from the previous study of numerical analysis of parallel flow heat exchanger (Pagare *et al.*, 2016). As shown in Figure 12, the phenomenon of LMTD and NTU were differentiated. With the varying levels of heat generation and heat transferred units, the chart below showed that LMTD inverses the NTU. This equation states that *Q* is the heat transfer, *U* is the over-all heat transfer coefficient and *Tm* is the median temperature.

$$Q = UA\Delta Tm \tag{13}$$

$$\Delta Tm = \frac{\Delta T1 - \Delta T2}{Log\left[\frac{\Delta T1}{\Delta T2}\right]} \tag{14}$$

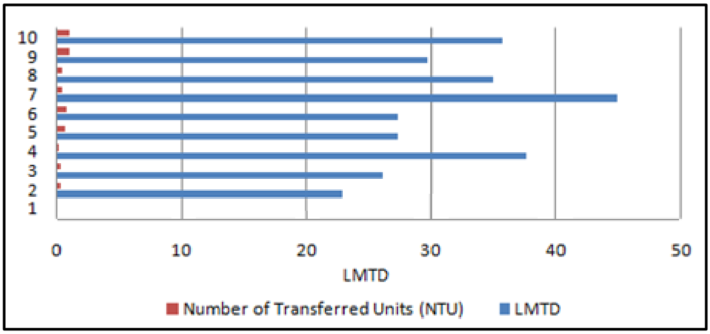

Figure 12. NTU and LMTD relation

3.4 Operating Pressure on Heat Addition

The relationship between of pressure drop in the fuel and heat addition in the system is shown in the Figure 13. Taken from the development of the numerical analysis model of a flow network for a plate heat exchanger (Yoon and Jeong, 2017), an operating pressure in relation to program analysis was limited to heat generation. However, in this study, the pressure drop in the fuel from the actual testing using air and stack testing equipment was calculated based from the atmospheric pressure and operating pressure.

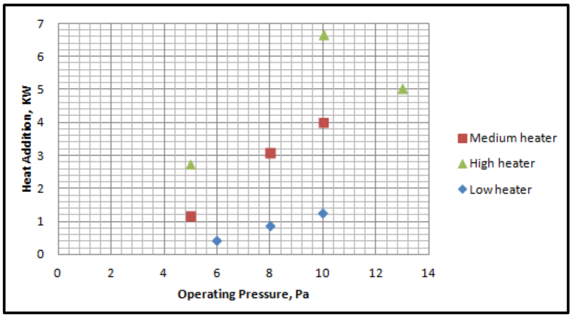

Figure 13. Operating pressure and heat addition relation

3.5 Fuel Oil Heat Requirement and Heat Transfer Effectivity

The evaluation of the heat requirement of fuel oil inside the serpentine coil was one of the objectives of this study. The result in Figure 14 shows that the required heat of the fuel oil increases as the number of transferred units reaches the maximum point. The higher and maximum heat released shows transfer units closer to 1 – this means that at that point the effect of heat transfer from air convection to copper tube to fuel oil was at its maximum. The heat added was effective as observed from the consistency of data from low heater to medium heater.

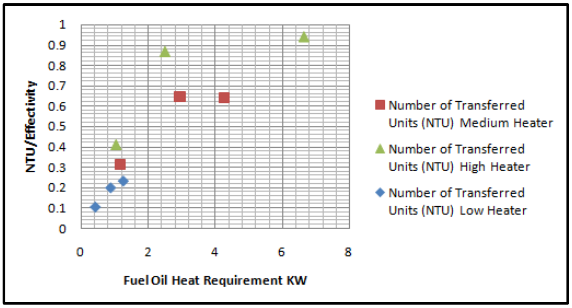

Figure 14. Heat requirement of fuel oil with respect to heat transfer effectivity

3.7 Heat Flow Simulation of Air as Heating Medium

The result of the simulation of heat flow at 122 iterations with following boundary conditions is shown in in Figure 15. The inlet temperature of 313 K (40°C) raised up to 330 K (57°C); thus, a temperature difference of 17. The heat was more concentrated at the lower part of the serpentine coil and was reduced as it left second baffle.

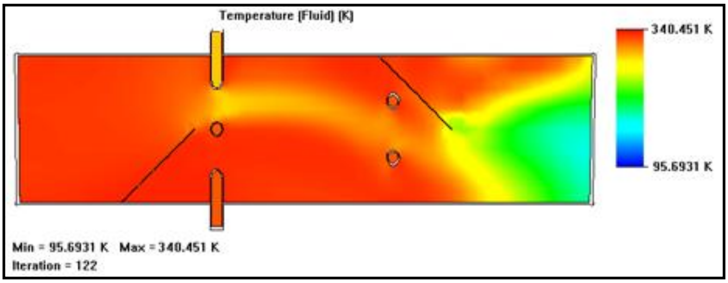

Figure 15. Heat flow simulation of air as it exchanged heat with the fuel oil

Figure 16 illustrated the heat flow trajectory. The heat concentration was at the bottom part of the coil having a revolving motion as it flowed to the second baffle.

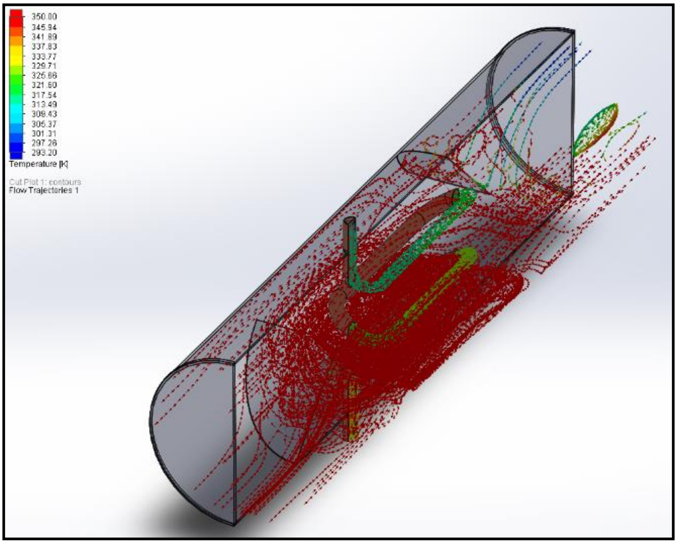

Figure 16. Isometric view of air's heat flow trajectory as it exchanged heat with the fuel oil

3.8 Velocity Flow Simulation of Air as Heating Medium

Figure 17 shows a velocity flow of air as it travels towards the x-axis giving a minimal velocity. The velocity started at 1.78 m/s then increased upon entry of the first baffle increased since the cross-sectional area of the pipe was reduced up to 50% of the total area. The temperature simulation showed a single loop at the bottom of the pipe, in this portion, the concentration of velocity took place; however, it was reduced and to continue to increase its velocity upon the exit through the second baffle.

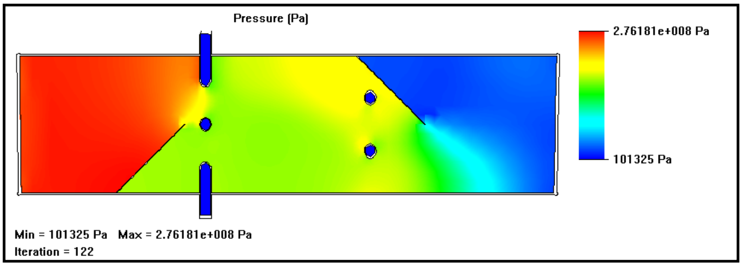

Figure 17. Pressure distribution as air flowed through the conveying pipe

Pressure flow trajectory shows a decrease in pressure of air travels through the conveying pipe as shown in Figure 18. Even if the temperature inside the serpentine coil increased, it reduced its pressure due to reduction of viscosity of the fluid and series of bend as it reached the bottom point.

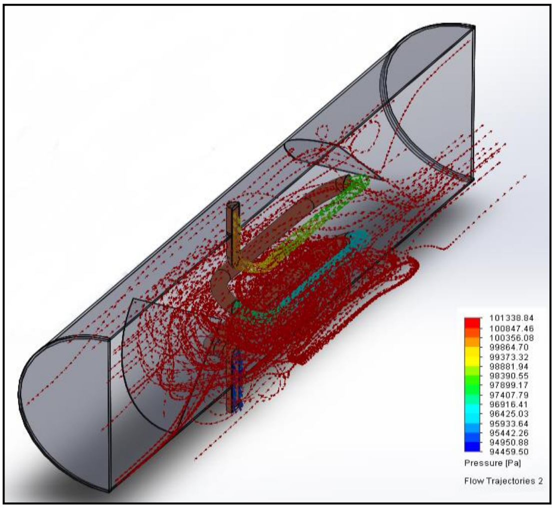

Figure 18. Isometric view of pressure trajectory lines as it conveyed the pipe and crosses the serpentine oil.

3.10 Heat Flow Simulation of Exhaust Gas Heating

Figure 19 shows a simulation of exhaust gas to heat the fuel oil with a maximum capacity of 353 K (80°C) and minimum capacity of 329 K (56°C) upon entry in the inlet. As the exhaust gas travelled slowly towards the x-axis, it reduced heat as it passed through the baffles. It also expanded as the heat passed through the serpentine coil.

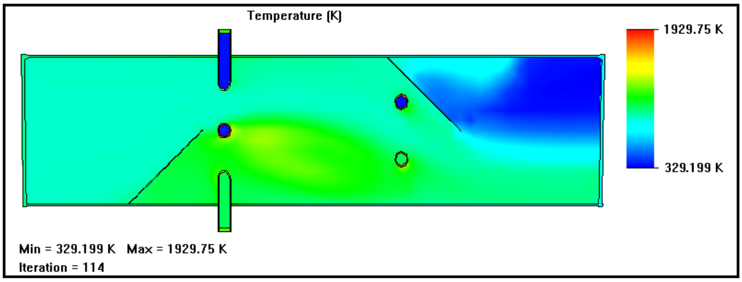

Figure 19. Heat flow simulation of exhaust gas as it exchanged heat with the fuel oil

In Figure 20, exhaust gases flowed through the conveying pipe and created a loop as it passed through serpentine coil. This was the portion where the heat concentrates as it continued to flow.

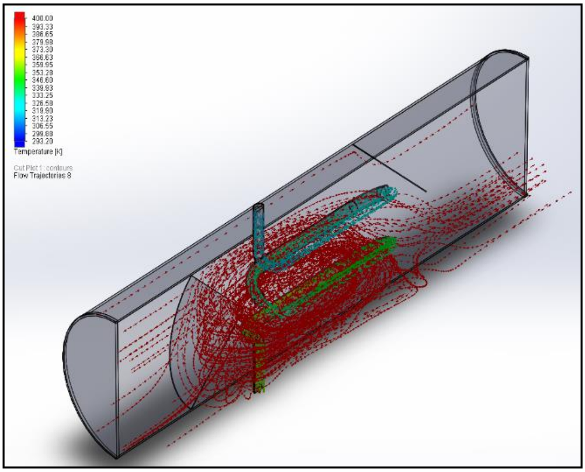

Figure 20. Isometric view of exhaust gas heat flow trajectory as it exchanged heat with fuel oil

3.11 Velocity Flow Simulation of Exhaust Gas

Figure 21 shows the velocity profile of heat exchanger using exhaust gas as heating medium. Velocity was reduced in the region where the serpentine coil was located and increased its speed as it reached the bottom part.

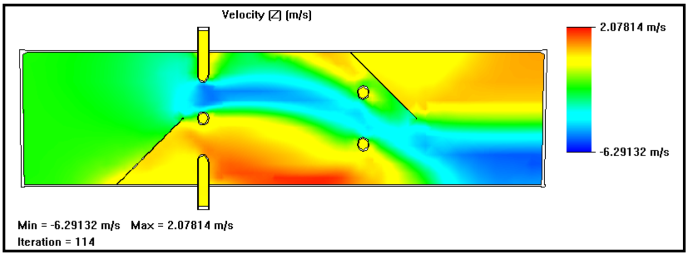

Figure 21. Velocity distribution inside the conveying pipe as it surrounded the serpentine coil

The trajectory flow of exhaust gas velocity was shown as it entered the duct pipe and flowed towards the x-axis. The trajectory flow revolved and formed a loop at the bottom part after the baffles. In Figure 22, velocity trajectory crossed the serpentine coil and travelled to the bottom then exited towards the second baffle.

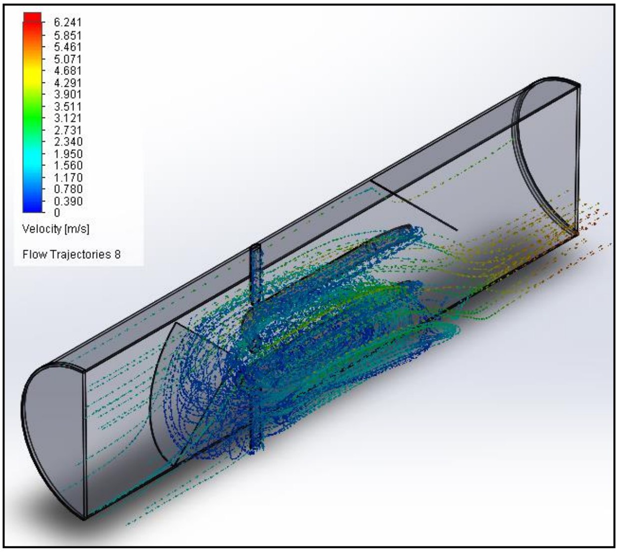

Figure 22. Isometric view of velocity flow trajectory as it passed the serpentine coil heat where the fluid to be heated flows.

3.12 Pressure Simulation of Exhaust Gas

Figure 23 shows the distribution of exhaust gas pressure as it flowed through the conveying pipe. The pressure decreased as it travelled along the baffles and serpentine coil. The pressure loss of the system caused to reduce the temperature.

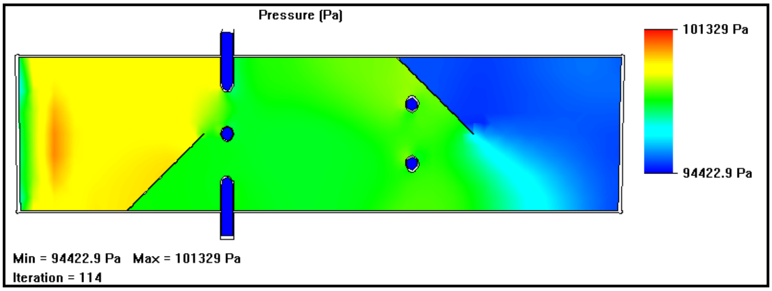

Figure 23. Pressure distribution as air flowed through the conveying pipe

The pressure flow trajectory decreased its pressure as it travelled the conveying pipe – the same with the fluid flow inside the serpentine coil as shown in Figure 24. The fluid inside the coil increased its temperature at the same time reduced its pressure. This is due to the reduction of viscosity and effect of heat on the fluid.

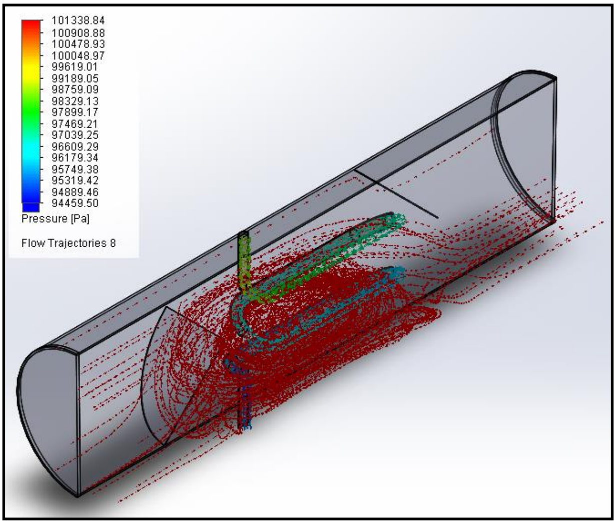

Figure 24. Isometric view of pressure trajectory lines of exhaust gas as it conveyed through the pipe crossing the serpentine coil.

4. Conclusions and Recommendation

The heat generated using exhaust gas increased the temperature. The temperature rise in the pre-heater decreased and data showed a reduction of viscosity at 79.3 % from inlet to outlet of the serpentine coil. The effect of fuel oil's viscosity is inversely proportional as temperature increases. The economic study on fuel oil pump energy would consume 0.35 liters of diesel fuel per day from 0.75 liters/day. If the company will allow the actual installation, a total fuel savings of 47% is expected since the pre-heater equipment consumes a lot of energy.

The study on energy conversion and waste heat utilization was performed in this paper and the bases of the project was to show the effect of designed heat exchanger of the element to be heated. This study is to look for alternative option on how to save the increasing cost of the fuel rather than replacing the pre-heating equipment. The passenger vessel's data on its main engine was carried out after the heat exchanger was fabricated. The utilization of heat and waste energy recovery was highly found on the exhaust gases and the best source of convective heating.

Theoretical and mathematical calculations were come up to design a serpentine coil heat exchanger assembly made with copper. This design provided an efficient thermal transfer on the fluid. The fabricated project has undergone a series of tests and software simulation of heat, velocity and pressure distribution. With this, the data and results showed a 57°C temperature of the aimed 60°C – it exceeded by 20°C temperature difference after a data simulation on the exhaust. The viscosity was reduced when the heat was applied in the fluid. The energy exerted and operating pressures of the system was taken. The NTU and LMTD concluded the effectiveness of the designed heat exchanger.

It is recommended to improve the accuracy of fluid flows; eliminate losses in the designed serpentine pipes due to series of bends. Furthermore, simultaneous temperature distribution for the testing and using of sealed fan to decrease the pressure drop should be made. Reconsideration of new structure of serpentine coil into U bended coil to decrease heat losses could also be employed. Also, sealing the heat exchanger with high thermal capacity rubber seal to prevent air leaks and time resist the high temperature released by the heater.

5. References

Chevron Marine Fuel Oils. (2018). Chevron Marine Fuels the Power of Human Energy. Retrieved from http://www.chevronmarineproducts.com/content/dam/chevronmarine/Brochures/Chevron_EverythingYouNeedToKnowAboutFuels_v3_1a_DESKTOP.pdf

Deshpande, R.S., & Bux, S. (2015). A Review on Performance of Diesel Engine with Heat Exchanger. International Journal of Engineering and Science Research, 5(5), 184-186.

Donaldson, F. (2018). Formula for Exhaust gas flow rate calculation. Retrieved from http://www.asia.donaldson.com/en/exhaust/support/datalibrary/1053747.pdf

Hossain, N., & Bari S. (2011). Waste heat recovery from exhaust of a diesel generator set using organic. Fluids School of Engineering, University of South Australia, MawsonLakes5095, Australia.

Nitonye, S. (2018). Machinery Space. Retrieved from http://www.Machineryspaces.com/diesel-alternator.html

Edwards, J.E. (2008). Design and Rating of Shell and Tube Heat Exchangers. Teesside, UK: I Design Ltd. Retrieved from http://www.cit-wulkow.chemstations.com/content/documents/Technical_Articles/shell.pdf

Pagare, A., Tripathi, K., & Choudhary, N. (2016). Numerical Analysis of Parallel Flow Heat Exchanger. Journal of Emerging Technologies and Innovative Research, 3(7), 57-62.

Potter, P.J. (1959) Power Plant Theory and Design. New York, NY: Ronald Press Co.

San, J.Y., Lin, G.S., & Pai, K.L., (2009). Performance of Serpentine Heat Exchanger: Part I - Effectiveness and heat transfer characteristics. Applied Thermal Engineering, 29(14-15), 3081-3087.

Simon, T.W., & Alshare, A.A. (2009) Simulations of flow heat transfer in a serpentine heat exchanger having dispersed resistance with porous-continuum models. International Journal of Heat and Mass Transfer, 53(5-6), 1088-1099.

Yoon, W., & Jeong, J.H. (2017). Development of numerical analysis model using a flow network for a plate heat exchanger with consideration of the flow distribution. International Journal of Heat and Mass Transfer, 112, 1-17.