Design and Modelling of a Waste Heat Recovery System for a 250KW Diesel Engine for Process Heating in the Energy Transition

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Abstract
Diesel engines have significant application in transport, agriculture and power generation as prime movers for both medium and heavy-duty machinery including electric generators in power plants. However, the engines convert less than 40% of fuel power to useful work with the rest being lost through the exhaust and cooling systems. Through waste heat recovery technology, the low grade heat in the cooling system can be recovered effectively with the organic Rankine cycle. The objective of this study is to increase the efficiency of a diesel engine for fuel economy and reduce CO_2 emissions through waste heat recovery from both the cooling and exhaust systems. Heat exchangers were proposed and designed for optimum heat recovery from both the exhaust and the coolant for a low temperature application in cereal drying. Shell and tube heat exchangers are designed and modelled using computer software. The amount of energy extracted from the exhaust is 90.5 KW while that from the coolant is 95 KW with the heat exchangers having an effectiveness of 0.68 and 0.58 respectively. The recovered energy is used to heat air up to 55ºC, which is directed into a cereal dryer which is designed for maize drying, but can be used for other cereals. At a drying cycle of 10 minutes, 58 kg of maize can be dried effectively.

Keywords- Waste heat, Heat exchanger, working mediums, Heat recovery, Cereal dryer

1. Introduction
There is a global commitment by the world community to reduce greenhouse gas emissions and mitigate against global warming and related consequences (Kabeyi & Oludolapo, 2020b). Engines loose significant recoverable quantity of energy in fuel through exhaust gases and the cooling system which can be recovered and put to useful application (Kabeyi & Oludolapo, 2020c, 2020d). There is also need to reduce fuel consumption because of polluting emissions associated with fossil fuel combustion that include SO_2, CO_2, NOx, particulates, and CO through efficiency measures and heat recovery techniques (Ravi, Vijayakumar, Kumar & Gunaseelan, 2015). Significant amount of diesel fuel power used in diesel engines is released to the environment as heat in the exhaust and cooling system (Kabeyi, 2019; Kabeyi & Oludolapo, 2020a). According to Talib, et al (2017) there is need to use technology to improve engine fuel economy without increasing fuel related carbon emissions. For an internal combustion engine, as much as 34% of waste energy in the exhaust can be utilized.

In gasoline engines up to 21 % of fuel energy lost through the exhaust can be utilized. Of the total energy in fuel supplied to an engine, 30 to 40% can be converted to useful mechanical power output (Tiwari, Vasnami, Kumar & Labana, 2017). Generally, an internal combustion engine releases 30-40% of the fuel energy from combustion through the exhaust to the environment and an almost equal amount through the engine coolant (Wilson John M. R., *et al.*, 2017). This energy is just sufficient for recovery and for use in many thermal applications with minimal heat losses in the designed waste heat recovery system (Milkov, Evtimov & Punov, 2012). Recovery of this heat would greatly reduce the overall amount of fuel required for both primary and auxiliary uses resulting in cost saving and in less production of pollutants like NO_X and SO_2 while producing the same power (Kabeyi & Oludolapo, 2020b, 2020c). Ultimately, waste heat recovery from engines is a strategy in mitigating against excessive use of fossil fuels which cause environmental degradation and can also be used in reduction of process heating costs and fuel energy costs. Bari & Hossan (2013) observed that the exhaust of a diesel engine can be used to supply extra mechanical power using the Rankine cycle with water as a working fluid with about 38% extra power potential with optimum pressure of about 30 bars. Figure 1 below shows the distribution of fuel energy in an internal combustion engine.

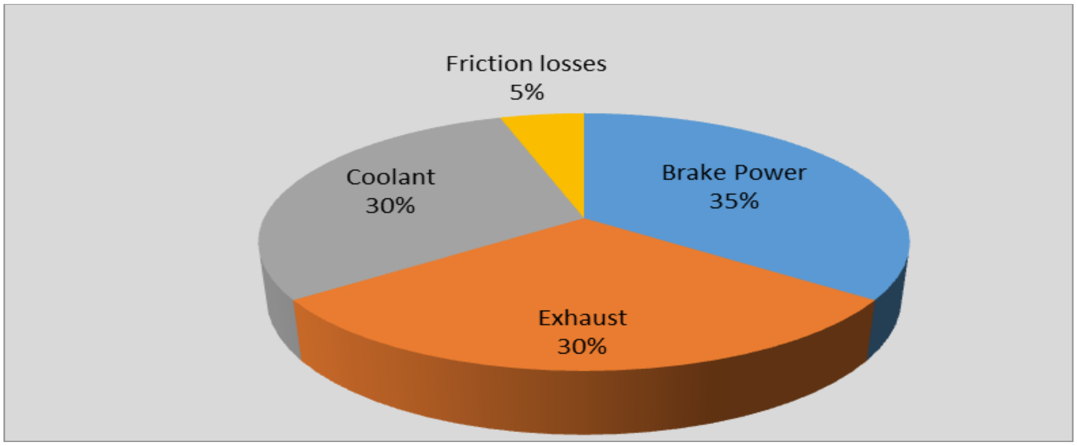

Figure 1: Fuel energy utilization by percentages for a diesel engine (Tiwari, Vasnami, Kumar & Labana, 2017)

From figure 1, it is noted that of the total fuel power going to the engine, about 30% is lost to the cooling system, about 30% is lost through the engine exhaust gases, 5% is lost to friction and other undetermined losses and on average 35% is converted to mechanical power. Waste heat from the exhaust can be recovered to generate extra power for process heating or mechanical application including power generation (Kabeyi & Olenwaraju, 2020d).

In this study, a review and analysis of waste heat recovery potential for a 250 kW diesel engine from both exhaust and cooling systems is done. It is assumed that such an engine can be used as a prime mover several farm based machinery and operations like milling, and cereal drying. The aim is to establish the waste heat potential of farm level as well as industrial activities like power generation using diesel engines so as to develop recovery models for investment in waste heat recovery for farm level agricultural and industrial activities (Jeremiah, 2018). This research focuses on the heat recovery through heat exchangers, where a working fluid is heated up by the energy extracted from the exhaust and coolant and used for cereal grain drying or similar thermal application.

2.0. Problem Statement

Engine manufacturers, environmental regulators, government and consumers have high motivation to mitigate against greenhouse gas emissions and increase engine efficiency because of the danger of greenhouse gas effect and global warming, depletion of fossil fuels and high fuel cost (Barry & Hossain, 2013). Maize, is a very important cereal crop for sub-Saharan Africa. Not only does it provide an avenue for preparing various types of food but also serves as a raw material for many industries. It is high yielding, readily digested, easy to process and comparably cheaper than most other cereals available in the market. It can also be processed into different forms, most popularly in the form of maize meal which makes up the staple food for a huge number of people in Africa (Kabeyi, 2020a) . Effective management of post-harvest factors such as moisture content, temperature, sanitation of storage facilities and aeration go a long way towards preserving grain and keeping it at safe for human consumption (FAO, 1983).

3.0. Waste Heat Recovery Systems

Waste heat to power (WHP) is the process of capturing heat discarded by an existing process and using that heat to generate electricity. WHP technologies fall under the WHR category. In general, the least expensive option for utilizing waste heat is to re-use this energy in an on-site thermal process. If it is not feasible to recover energy from a waste heat stream for another thermal process, then a WHP system may be an economically attractive option (Kabeyi, 2020b).

The technology for waste heat recovery in internal combustion engines facilitates recovery of low grade waste heat from the cooling system and high grade heat in the exhaust system. The organic Rankine cycle is the best option for low grade heat recovery while various other options are available for high grade heat recovery. High grade waste recovery options include turbocharger, turbo compounding, heat pipe, air conditioning, the Rankine cycle, thermoelectric generator, thermal storage, Rankine cycle turbine. The main determinants of waste heat recovery from engine exhaust are the engine speed and exhaust temperature (Talib, Herawan, Tahir, Putra & Shamsudin, 2017).

3.1. Waste heat recovery technologies

According to the US department of energy, various feasible technologies are available for recovery of waste heat. They include

i.) Rankine Cycle (RC) - The most common example of the Rankine cycle is the steam turbine, or steam Rankine cycle (SRC). In a SRC system, the working fluid is water, and steam is created to drive a turbine.

ii.) Organic Rankine Cycle (ORC) - Organic Rankine cycle (ORC) systems are similar to SRC systems, but are typically used at lower temperatures, and instead of water the working fluid is a hydrocarbon, hydrofluorocarbon, or ammonia.

iii.) Kalina Cycle (KC) - The Kalina cycle is a variation of the Rankine cycle, using a binary fluid pair as the working fluid (typically water and ammonia), and has the potential to have higher efficiency than the SRC.18

iv.) Supercritical CO_2 Cycle - Another variation of the Rankine Cycle is the supercritical CO_2 (sCO_2) cycle, which utilizes carbon dioxide in place of water/steam for a heat-driven power cycle. The QTR Technology Assessment 4.R Supercritical Carbon Dioxide Brayton Cycle examines sCO2 in more detail (US Department of Energy, 2015).

3.2. Emerging or Developing Waste Heat Recovery Technologies

There are various technologies being developed and tested at the laboratory or pilot scale in many different countries to be used in waste heat recovery. The current status of the technology or product development depends on the local energy situation in terms of cost and availability or access as well as availability of support from the local governments or funding agencies (Barasa, 2020; US Department of Energy, 2015). The, the following emerging WHR research topics and technologies are under investigation in many countries;

i.) Conversion of waste heat into a flexible and transportable energy source such as electricity

ii.) Heat recovery from high-temperature gases with large amounts of contaminants such as particulates, combustibles, and condensable vapors (organic, metallic, or nonmetallic materials)

iii.) Heat recovery from ultra-low temperature sources, primarily lower than 250°F

iv.) Heat recovery from low- to medium-temperature exhaust gases or air with high moisture content to recover the latent heat of water vapor

Tremendous research has shown that some advanced technologies can be used to further increase waste heat recovery efficiency through use of concepts such as turbo-compounding, thermoelectric generation and thermodynamic cycles (Milkov, Evtimov & Punov, 2012). Turbo-compounding causes increase in backpressure and pumping loss (Bari & Hossain, 2013) which can cause fatalities to the engine. Low efficiency coupled with the high cost of materials in thermoelectric generation renders it not applicable to such small scale (Jumade & Khond, 2012). Heat transfer from exhaust needs a heat exchanger and a working fluid for production of steam, which is expanded in the steam turbine through the bottoming process to produce mechanical rotation of the turbine shaft. This shaft is coupled to the generator shaft and results in production of power. The Exhaust Gas Recirculation (EGR) and the exhaust gas line were identified as the best sources of waste heat for recovery. In some studies, organic Rankine Cycle (ORC) with ethanol as the working fluid have been realized. The ORC maintained the pressure and temperature constant using evaporators of varying geometry and a condenser with variable bypass coolant (Henriques, 2011).

4.0. Organic Rankine Cycle

Although significant improvement has been made on diesel engines to improve their efficiency, a considerable amount of heat is still rejected to the tune of 50% of the total energy in fuel. The organic Rankine cycle has proved to be one of the most effective solutions in waste heat recovery (Amicabile, Lee & Kum, 2015). The use of organic Rankine cycle for waste heat recovery for electric power generation in trucks realize up to 10% savings in fuel used (Tiwari, et al, 2017). An ORC is made of same components as a traditional steam Rankine cycle. These are namely a pump, evaporator, a turbine or expander and a condenser. The major difference comes from the choice of working fluid: water is replaced by an organic component. Figure 2 below shows the basic construction of an organic Rankine cycle.

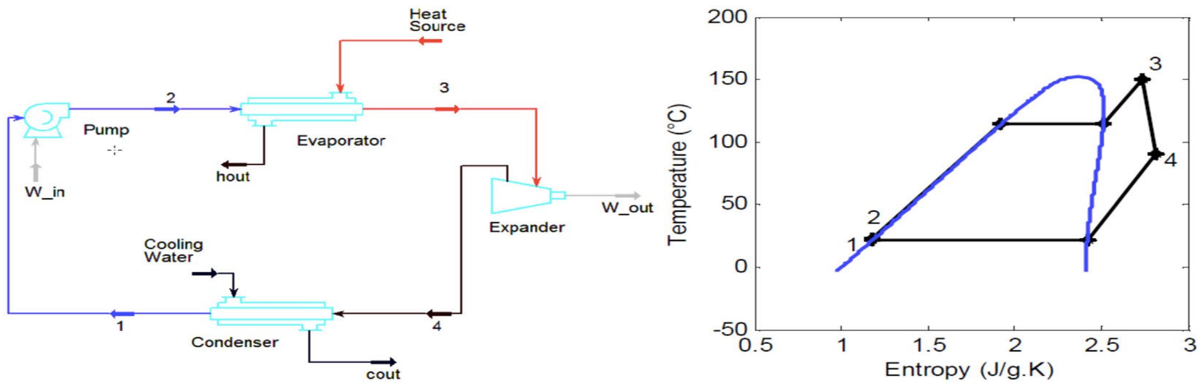

Figure 2: Organic Rankine cycle (Markides, 2015)

Figure 2 illustrates the construction of organic Rankine cycle with major elements being cooling water for condenser, pumps, expander, and evaporator in a closed circuit. The cycle is presented on a T-S diagram to show the relationship between entropy and temperature.

4.1. Organic Rankine Cycle Process

The cycle of (ORC) consists of the main parts being expander, evaporator, condenser and pump and but does not need a steam vessel and boiler and has a heat exchanger for processes such as reheated, superheated and evaporation found in a conventional steam Rankine cycle (Quoilin, 2011). A schematic diagram of the processes is shown in figure 3 and corresponds to the following events.

1-2: In this process, the working fluid is pumped from the condenser into the evaporator and raising its pressure respectively.

2-3: Heat addition takes place in the evaporator to heat the working fluid before enter the expander.

3-4: The operating fluid expands in expander and the mechanical energy is converted into electric.

4-1: The working fluid from the expander goes to the condenser where it is condensed and the condensate is recycled and the whole process is repeated over and over again.

The choice of a heat source first decision to make in in the design of an organic Rankine cycle for engine waste heat recovery. This is followed by selection of the best working fluid which depends on the heat source and potential power output (Chen, Goswani & Stefanakos, 2010). The selection of a working fluid is followed by optimization which involves formulation and solving of thermos-economic optimization problem (Quoilin, Declaye, Tchanche & Lemort, 2011).

4.2. Working Fluids

It is challenging to select the best fluid to satisfy perfect conditions for heat recovery which then calls for compromise. The commonly used criteria is the thermodynamic and environmental criteria.

4.2.1. Thermodynamic criteria

The molecular complexity defines the shape of the T-s diagram and is therefore important in working fluid selection. Dry fluids and isentropic fluids are fluids often selected for application in organic Rankine cycles because of their ability to avoid the wet phase during expansion especially at the end of expansion. Fluids with high density are preferred so as to control the size of the evaporator and expander (Amicable, Lee & Kum, 2015). Coolants like R11, R141b, R113 and R123 tend to exhibit superior thermodynamic properties than other (Tawiri, et, al., 2017). Results show that the best performance is provided by the regenerative subcritical cycle with Ethanol, while the solution with minimum capital cost is the subcritical cycles with Ethanol but without a recuperator (Amicable, Lee & Kum, 2015).

4.2.2. Environmental and safety criteria

Environmental criteria and safety factor which include global warming potential rules out R-11, R12, R-113, R-114 and R-115. R124 and R22 are also being phased out hence may not be considered for selection (Amicable, Lee & Kum, 2015). According to Tawiri, et al (2017) R11, R141b, R113, R134 and R123 manifest slightly higher thermodynamic performances but, R245fa and R245ca are the most environment-friendly working fluids for engine waste heat-recovery applications(Moses, 2018). The optimal control principle of ORC under the transient process is discussed

4.3. Design

The design process consists of three steps, namely: heat source selection, candidate fluid selection, and thermodynamic cycle optimization. For the designer to select the best waste heat source, the available energy and other practical considerations of available heat source options are compared. Among others, the Exhaust Gas Recirculation (EGR) cooler has shown to be the best heat source, and therefore is often used in engine heat recovery. On working fluid selection for engine waste heat selection, Ethanol, Pentane, R 134 and R245fa are selected as the best candidate working fluid. Four types of cycle layouts are considered in comprehensive ORC optimization,
i.) subcritical cycle without a recuperator,
ii.) Subcritical cycle with a recuperator,
iii.) Supercritical without a recuperator, and
iv.) Supercritical cycle with a recuperator.

4.3.1 Diesel engine specifications

Most common diesel engines in small utility power generation have a power output of 250kw hence their availability and the ease of modification. These engines run on a four stroke combustion process developed by the German engineer Rudolf Diesel in the 19th century (Rissman & Kennan, 2013), Four stroke engines involve the piston moving up four times within the cylinder for a single combustion cycle. These strokes are intake stroke, compression stroke, power stroke and the exhaust stroke. Exhaust stroke drives out the combustion products out of the combustion chamber through the exhaust valve to the exhaust manifold.
Due to high temperatures of the products, this work proposes a re-route of these products through a bypass to a heat exchanger where heat can be extracted from them and combined with that extracted from the hot coolant to be used in cereal drying process. The specifications for the engine under investigation are shown in table 1 below;

Table 1: Engine specifications (Mantrac Kenya Limited, 2019)

NAME	C9 ACERT
MODEL	CAT (caterpillar)
ENGINE POWER (BKW)	254
FUEL TYPE	DIESEL
COMBUSTION	DIRECT INJECTION (DI)
INJECTION TYPE	COMPRESSION IGNITION (CI)
COMPRESSION RATIO	16.1
TURBOCHARGER	SINGLE
COOLING SYSTEM	WATER COOLED

From table 1, the specifications of the engine used in the study are presented as a turbocharged and water cooled Caterpillar, compression ignition engine of capacity 254 kW of brake power with compression ratio of 16 to 1, running on diesel fuel.

4.3.2 Materials and working fluids

Materials used in the construction of the heat exchanger parts are shown below in Table 2 while for proper operation of the exchanger, the following properties tabled in Table 3 are important.

Table 2: Table of materials (Rissman & Kennan, 2013)

Part	Material	Reason for choice
Front header	Galvanized steel plate (thickness 4mm)	Corrosion resistant, easily machineable
Rear header	Galvanized steel plate (thickness 4mm)	Corrosion resistant, easily machineable
Tubes	Galvanized steel/ copper	High thermal conductivity, corrosion resistant, non-reactive with most cleaning agents. However for economic reasons, steel tubes are preferred.

Baffles	Galvanized steel plate (thickness 4mm)	Corrosion resistant, easily machineable, high stiffness constant
Shell	Galvanized steel plate (thickness 4mm)	Corrosion resistant, high thermal expansion coefficient corresponding to heat exchanger materials.

Table 2 is a summary of material specifications used in the proposed heat exchanger construction for the various parts, namely front header, rear header, tubes, baffles and the heat exchanger shell which are the main parts. The materials should generally be corrosion resistant while heat exchanger materials should additionally have high thermal conductivity and preferably lower thermal expansion coefficient. Galvanized steel or copper tubes have diameter of ¾ inches or 19mm the dimensions of which is subject to design calculation. The operating properties of the fluid have a major influence on the efficiency, design and size of the heat exchanger (Milkov, Evtimov & Punov, 2012). While water has high efficiency in the case of high temperature source, organic fluids have high efficiencies when using a low temperature source. Therefore, the temperature of the heat source largely determines the selection of the working fluid (Bari & Hossain, 2011). As a result, this study involves water as a working medium for the exhaust heat exchanger since it's a high temperature source and R134a as the working medium in the coolant heat exchanger owing to the small change in temperature of the coolant.

Table 3: Properties of heat exchange media (Bari & Hossain, 2011).

	Heat capacity (C_P) kJ/KgK	**Dynamic viscosity(μ) $10^{-6}\ Kg/ms$**	**Thermal conductivity(κ) $10^{-3}\ W/mK$**	**Density(ρ) Kg/m^3**
Water	4.184	486	650	985.2
R134a	0.8283	11.26	0.012	17.4
exhaust	1.0539	30	47.31	0.5774
Air	1.0049	18.46	26.24	1.177

Table 3 shows the propertied of the working fluids i.e. water, refrigerant R134a used to extract heat from the cooling water in the cooling system, exhaust gas with heat from the engine, and air used for heating cereal. The properties compared are the heat capacity where water has the highest while the R134a has the lowest. R134a has the lowest conductivity hence better thermal/heat carrier than water which has highest conductivity.

4.4. Design overview

A major design criterion in the design of a waste heat recovery system is the proper selection of the heat exchanger and working mediums with optimum conditions. The objective of this research is to design a waste heat recovery system by optimizing designs for the exhaust gas heat exchanger and the coolant heat exchangers and then designing a cereal dryer for use of the recovered heat to supplement the conventional fuels such as Methane and the industrial diesel oil (IDO) used to provide heat for cereal drying (Kabeyi & Oludolapo, 2020d). The schematic representation of the heat recovery system working principle is shown in Figure 3 below, while the designed schematic dryer is shown in Figure 4

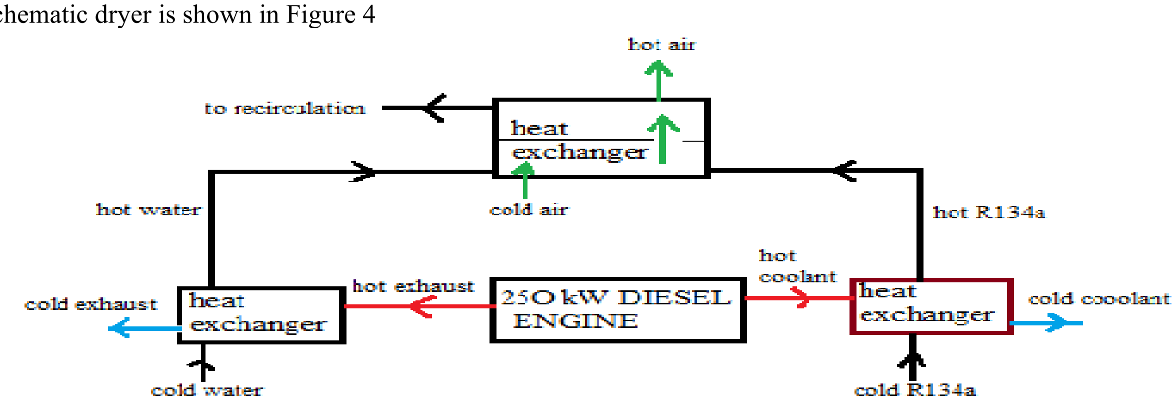

Figure 3: Schematic representation of the working principle (Authors Conceptualization).

Figure 3 shows the proposed design where the exhaust is directed to a heat exchanger with water as a coolant. The engine coolant is also directed to a heat exchanger using R134a as the coolant. The coolants discharge the extracted heat to a third heat exchanger which heats air for use in process heating or drying application. Both coolants are recirculated within their systems.

With such design of the dryer as shown in Figure 4, this study will result in reduced dependence on methane or industrial diesel oil (IDO) used in powering the burners for production of hot air used in cereal dryers.

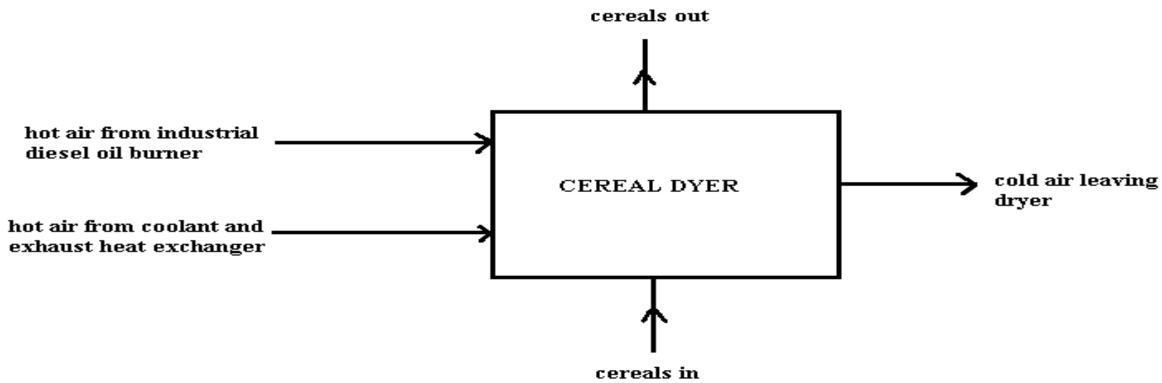

Figure 4: Schematic design of the dryer (Authors Conceptualization).

Figure 4 shows how the extracted waste heat can be used to dry cereals with additional heating from other sources to supplement the heat from the engine effectively reducing demand on the main source of drying heat and saving on energy costs and overall environmental impact.

4.5. Waste heat energy potential

The quantity of heat contained in both the exhaust and the coolant is a function of both the temperature and the mass flow rates (Surwase & Farkade, 2016).

$$Q = \dot{m} C_P \Delta T$$

Where Q is the heat loss (KJ/s);
m is the mass flow rate (kg/s);
Cp is the specific heat
And ΔT is the temperature gradient in K.

It is important that the sink temperatures be below the source temperatures in order to enable heat recovery. The magnitude of the heat recovered is directly proportional to the temperature change between the source and the sink temperatures. This change also influences the choice of the working fluid as earlier stated. Variations of engine parameters with change in loading condition are shown in figure 5 below;

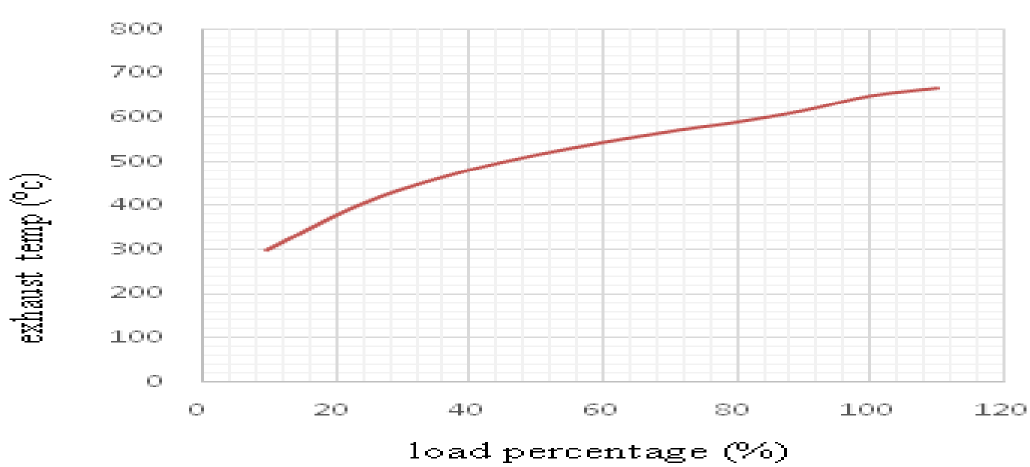

Figure 5: Variation of exhaust gas temperature with load (Mantrac Kenya Ltd, 2019)

From figure 5 above, it is noted that exhaust temperature increases with the engine load. These implies that the exhaust has more recoverable heat energy at higher loads although more fuel is also consumed by the engine. Figure 6 below shows the variation of heat rejected to the exhaust and cooling water with percentage loading.

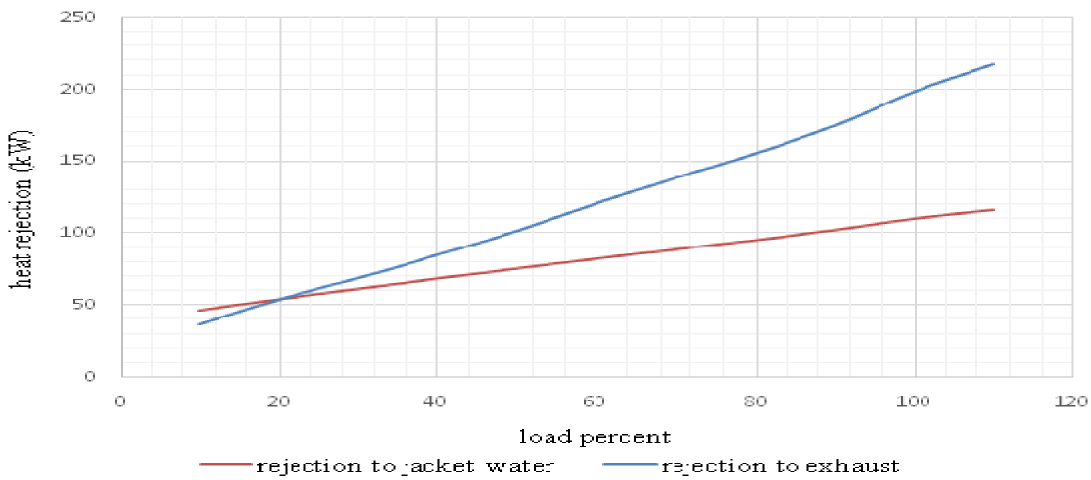

Figure 6: Variation of heat rejection with change in load (Mantrac Kenya Ltd, 2019)

Figure 6 shows the proportionate distribution of engine waste heat in the cooling system and exhaust with engine load condition. At low loads below 20%, most of the waste heat of the engine is in the cooling system. Above 20%, there is more waste heat in exhaust than the cooling systems

4.6 Heat Exchangers Design

Preferred heat exchangers are of the shell and tube family because of their high effectiveness as compared to the plate type heat exchangers (Rajput, 2012). Combined heat exchanger will consist of two chambers, one for air preheating using heat extracted from the coolant and the other for final heating using heat extracted from the exhaust gas. Engine's exhaust and coolant temperature data is used to optimize design of the shell and tube heat exchangers through utilization of the tubular exchanger manufacturers' association (TEMA) standards. Design effects of heat exchanger parameters such as the diameter of the shell, number of tubes, length of the heat exchanger, pressure drop are investigated and the final models of the heat exchangers proposed. Specifications of the proposed shell and tube heat exchangers are shown in table 4.

Table 4: Heat exchangers specifications (authors' parametric design)

	Exhaust heat exchanger	Coolant heat exchanger	Combined heat exchanger
Length of heat exchanger(m)	3.2	4.2	2
Shell diameter(mm)	304.8	203.2	438.15
No of tubes	52	21	112
Tube inner diameter(mm)	20.1	21.184	21.184
Tube outer diameter(mm)	25.4	25.4	25.4
Baffle spacing(mm)	152.4	101.6	219.8
No of passes	2	1	1

From table 4, it is noted that the proposed heat exchangers are three, namely the exhaust heat exchanger which extracts heat from engine exhaust with water as the coolant, coolant heat exchanger which extracts heat from the engine cooling system and it has an organic fluid as coolant, and combined heat exchanger, which receives recovered heat from the two coolants and transfer it to air which is used for drying the cereals or grains.

5.0 Waste Heat Cereal Dryer

Cereals can be defined as edible grain of grass family e.g. maize, wheat, rice, sorghum, millet, and oats. An important step before storage of grains for future use is drying to remove excess moisture (Mckevith, 2004). Food drying or dehydration is the process of removing water from food by circulation of hot air through it. This process effectively prohibits growth of enzymes and bacteria which is necessary to preserve cereals. The various drying methods available include sun drying, solar drying, freeze drying, and oven drying (Ahmed, et al, 2013). In this study, drying is done by hot air with heat extracted from the engine cooling and exhaust systems.

5.1. Cereal grain dryer design

To design a cereal dryer, outdoor air temperature of 24^{o}C and the relative humidity (RH) of 69%, which are the average values in a typical town are used (FAO, 1983). The air undergoes sensible heating to 55^{o}C. From the psychrometric chart, relative humidity of the incoming air is obtained as 12%. With the initial moisture content of maize being at 20%, air volume required to remove 1kg of water is 221.71m^3/kg vapour which translates to air volume flow rate of 1.2937m^3/s. For a 10 min discharge, the total volume of air required is 776.22m^3. This volume removes 4.975kg of water, which translates to 58kg of maize in one drying operation. Taking density of maize to be 720kg/m3, the volume of maize, which equals the volume of the dryer, becomes 0.081m^3. To accommodate for closing lids and a hopper, the total volume is taken as 1m^3. This optimized design specifications are presented below in Table 5.

Table 5: Maize Cereal dryer specifications (authors' optimized design)

Diameter (m)	1.13
Height (m)	1
Capacity (kg)	58
Discharge time (min)	10

From table 5, the specifications of the maize dryer are summarized as capacity 58 kg for a cycle of 10 minutes.

5.2. Pump Selection

Pumps are provided to facilitate fluid flow at the required pressure and flow rates. Water and air pumps are selected by use of flow rate-head pump performance curves. R134a has enough pressure when vaporized but requires a 220V, 600Wcompressor to boost pressure when it leaves the combined heat exchanger. All the pumps will be centrifugal pumps. The water pump required to provide a volumetric flow rate of $3.327 \times 10^{-4} m^3/s$ ($1.198 m^3/hr$), at a net head of 11.369m, has a power rating of 1.5 kW at 1450rpm. The air pump required to provide a volumetric flow rate of $1.2937 m^3/s$ at a pressure drop of $2.25\ kpa$ has a power rating of 2.2KW at 2900rpm.

6. 0. Conclusion

Waste heat recovery can be applied on engine systems with sufficient power output for economic heat recovery investment. In this study, recovered energy from the exhaust is 90.5KW while that of the coolant is 95KW with the effectiveness of 0.68 and 0.58 respectively. This change with the varying engine load and engine speeds. The results are analyzed at 80% load. This is the recommended load, by the engine manufacturer. Cooling medium leaving coolant heat exchanger has set temperatures to avoid temperatures dropping beyond the recommended engine jacket cooling temperatures, which could otherwise result in ineffective engine cooling because of under cooling. The design temperatures are 501.3℃ for the exhaust and 89℃ for the coolant, with the minimum temperature of recovery being 177℃ and 24℃ respectively. However, the design temperature for the exhaust is only realized at 80% engine load. For the heat exchanger to have a high effectiveness, the design engine load range can be set at 70-90%. When the engine is operating under an engine load outside the range, a valve-operated by-pass channel will release the exhaust to atmosphere, without passing through the heat exchanger. The designed cereal dryer can dry 58kg of maize in one single operation with a discharge time of 10 min. The inlet temperature of air is 55^{0}C and the discharge time will vary with the moisture content in the cereals, with a higher discharge time for moisture contents above 20%.

7.0. Recommendations

The use of engine waste heat recovery should be enhance with more research into efficient recovery technologies and systems. Investment will remain viable when fuel costs remain high and governments put in place penalties and restrictions to CO_2 emissions. Therefore policy initiatives are necessary to increase attractiveness and viability of waste heat technologies. These technologies play a critical role in the energy transition by limiting consumption of fossil fuels and reducing the electricity demand in several agricultural and industrial processes.

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