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Grain Drying Simulation in a GT-380 Dryer using Energy Recovered from ICE Exhaust

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Abstract : *This research primarily addresses the energy problem as experienced by farmers who use the GT 380 recirculating batch dryer for maize grain drying. The study used a 4.7 hp (3.5 kW) single cylinder, four-stroke, multi-fuel engine which was operated on diesel and biodiesel fuels. The objective of the study was to simulate the amount of maize grain that could be dried with recovered energy at various engine speeds and loads. For the purposes of estimating the amount of maize grain that could be dried with the recovered energy, specifications of the GT 380 recirculating batch dryer were used. The dryer had a rated capacity of 1900 kg/h. Determination of mass balances for dry matter and water were done using grain drying models. The main contribution of this study, in addition to the possibility of avoiding contact with dangerous propane, is in the possible minimization of energy costs by using less propane or none through the utilization of the recovered energy from exhaust gases. Through simulation, about 600 grams per hour and 700 grams per hour of maize grain could be dried with the recovered energy when the engine was operated on diesel and biodiesel respectively.*
Keywords: *Exhaust Gases Energy, Maize Grain Drying, Propane, Recirculating Batch Dryer, Simulation*

I. Introduction

Grain will normally be harvested at a moisture content of 18% to 25% wet basis, although it can be substantially higher or lower depending on many factors such as the stage of maturity, season, weather pattern and drying facilities. With good ventilation through the store, the grain can be harvested just after it is ripe (around 30% moisture content for maize) but most drying methods allow some of the drying to take place naturally while the crop is still standing in the field. For maize, the tradition in most parts of Kenya is to leave the crop in the field until the moisture content has fallen to around 18%. When the moisture content of the produce reaches equilibrium with the humidity of the ambient air, drying will stop. Maize will dry down to approximately 13% moisture content. Most farmers who practice mechanized agriculture use GT 380 dryers. This is a recirculating batch, cross-flow grain dryer with an axial fan, propane burner and cylindrical grain chamber enclosing the air plenum. The grain is fed into the bottom of a vertical auger by the grain agitator and continuously recirculated from the bottom to the top of the dryer. The dryer is power take off driven by a stationery tractor while its propane burner heats outside air forced by an axial fan past the burner into the air plenum and through the grain for complete drying of the grain.

Tractors have many applications but their operation can be divided into two regimes: transportation and work in the fields. In the fields the tractor runs with constant speed from one to the other side of the field then it takes some time to turn at the end of the field. This cycle is repeated many times. The constant speed of the tractor means that the engine runs at an almost constant load. The fuel consumption, engine power, engine efficiency and the enthalpy of the exhaust gases are constant. According to [1] the constant quantity of waste energy is produced during 80% of the time when the tractor works in the fields. [2] demonstrated that the energy balance can be made through a comparison between: the energy put in with the fuel, the energy converted in the effective power, the energy lost through friction, the energy lost in the cooling system and the energy lost with exhaust gases. The energy of the exhaust gases is calculated by the enthalpy which goes out from the cylinders trough the exhaust valves.

As in every technical application, diesel engines for agricultural machinery have their own typical features which have to be well known in order to understand the issues they are connected to. The most typical feature of a tractor is the fact that, in several applications, power consumption is not strictly related to tractor displacement. It was experimentally demonstrated by [3] that during working operation most of power absorption is in fact related to the working equipment pulled by the tractor. This is possible, thanks to a second shaft, directly connected to the engine and coaxial with tractor shaft, that transfers mechanical energy from the engine to the agricultural equipment. The two shaft movements are normally independent, which means that it is possible for the tractor to move while the equipment is not working, as well as the latter to do his job while the tractor is not moving [4]. The shaft connection between the tractor and its equipment is generally placed beside the vehicle and it is called power take off (PTO). This feature is important in order to understand engine's transient behavior. One of tractors' specific features is, in fact, their particular kind of transient operations. Tractors are generally used alternatively for two different goals, each having its specific features: on the field, for pulling and giving energy to agricultural equipment and on the road or on the field, for transporting goods. The main difference lays clearly in load factor variation with time as demonstrated by [5]. In fact, normal operations of agricultural machines on the field involve a periodical variation for engine load: full-load operation, when tractor is moving with its equipment working and partial-load operation, typically in maneuvering operations, when equipment is not working.

Despite the high level of development of the engine systems and controls, the maximum efficiency of 40% is reached in certain operation points; most of the time, engines run with efficiencies of 15% to 35%. It means that more than 60% of the fuel energy is lost. Part of the lost energy is in form of heat in the exhaust system. The expelled heat results into undesirable entropy rise in the environment. There is need therefore to develop strategies to reduce engine waste heat emission into the environment through energy recovery and subsequent utilization. Use of the recovered exhaust energy in applications such as maize grain drying in the GT 380 recirculating batch dryer is beneficial in a number of ways: propane heating costs associated with the dryer is minimized; and contact with dangerous propane is avoided thus, solving the propane handling challenge - operators of the dryer have to wear rubber gloves and eye protection while connecting the rubber hose to liquid propane. Moreover, studies on total energy distribution from an internal combustion engine has shown that out of the possible 100% fuel energy content in an engine, 35% is useful as brake power, 30% is lost in the cooling system, 5% is lost through radiation and approximately 30% is lost through the engine exhaust [6]. This research was limited to the recovery of energy only from the exhaust gases of a single cylinder four stroke multi-fuel engine. The recovered energy was used to estimate the amount of maize grain that could be dried from a moisture content of 25% to 13% wet basis. The research did not cover heat recovery from the cooling system which was another major route for heat loss (about 30%) from a compression ignition engine.

II. Materials and Methods

The study used a 4.7 hp (3.5 kW) single cylinder, four-stroke, multi-fuel engine which was operated on diesel and biodiesel fuels. A pipe calorimeter with a volume of 0.06 m3 was used to determine the changes in exhaust gases energy. Thermocouple temperature sensors and transmitters were used for temperature measurement. Data was obtained for: air and fuel consumption; exhaust gas to calorimeter inlet temperature; and exhaust gas from calorimeter outlet temperature. The specific heat capacity of exhaust gas was used as 1.006 kJ/kg·K. The recovered energy was used to estimate the amount of maize grain that could be dried from a moisture content of 25% to 13% wet basis. For the purposes of estimating the amount of maize grain that could be dried with the recovered energy, specifications of the GT 380 recirculating batch dryer were used. The dryer had a rated capacity of 1900 kg/h. Drying air forced by a fan past a propane burner entered the air plenum through the grain chamber to dry the grain at an inlet temperature of 45℃. The drying air exited the dryer at an outlet temperature of 25℃ with a relative humidity (∅) of 78%. These conditions were used in a psychrometric chart to determine other air properties. The aim of the research was to simulate maize grain drying from initial moisture content(m_i) of 25℃ wb to a final moisture content(m_f) of 13℃ wb. Initial moisture (M_i) and final moisture content (M_f) on dry basis were determined from (1) and (2).

$$M_i(db) = \frac{m_i(wb)}{1 - m_i(wb)} \tag{1}$$

$$M_f(db) = \frac{m_f(wb)}{1 - m_f(wb)} \tag{2}$$

Determination of mass balances for dry matter and water were done using (3), (4), (5) and (6).

$$\dot{m}_{wi} = Rated\ Capacity \times m_i(wb) \tag{3}$$

$$\dot{m}_{dmi} = \dot{m}_{dmf} = Rated\ Capacity - \dot{m}_{wi} \tag{4}$$

$$\dot{m}_{wf} = \dot{m}_{dmf} \times M_f(db) \tag{5}$$

$$\Delta\dot{m}_w = \dot{m}_{wi} - \dot{m}_{wf} \tag{6}$$

Where:

$\dot{m}_{wi}$ =initial mass flow rate of water $\left({kgH_2O}/{h}\right)$

$\dot{m}_{wf}$ =final mass flow rate of water $\left({kgH_2O}/{h}\right)$

$\dot{m}_{dmi}$ =initial mass flow rate of dry matter $\left({kgdm}/{h}\right)$

$\dot{m}_{dmf}$ =final mass flow rate of dry matter $\left({kgdm}/{h}\right)$

$\Delta\dot{m}_w$ =change in mass flow rate of water $\left({kgH_2O}/{h}\right)$

Moisture gained by each unit mass of dry air was determined from (7).

$$\Delta\omega = \omega_f - \omega_i \tag{7}$$

Where:

$\Delta\omega$ =change in each unit mass of dry air $\left({kgH_2O}/{kgDA}\right)$

ω_f =final unit mass of dry air $\left({kgH_2O}/{kgDA}\right)$

ω_i =initial unit mass of dry air $\left({kgH_2O}/{kgDA}\right)$

Mass flow rate of dry air was determined from (8) and energy required to dry 1 kg of maize grain was determined from (9). The amount of maize grain (kg/h) that could be dried with the recovered energy from the exhaust gases was determined from (10).

$$\dot{m}_{DA} = \frac{\Delta\dot{m}_w}{\Delta\omega} \tag{8}$$

$$Q_r = \frac{h \times \dot{m}_{DA}}{Rated\ Capacity} \tag{9}$$

$$Grain\ Dried = \frac{Q_R}{Q_r} \tag{10}$$

Where:

$\dot{m}_{DA}$ =mass flow rate of dry air $\left({kgDA}/{h}\right)$

Q_r = energy required to dry 1 kg of maize grain $\left({kJ}/{kg}\right)$

h =enthalpy at saturation $\left({kJ}/{kgDA}\right)$

Q_R =energy recovered from exhaust gases$\left({}^{kJ}/_{h} \right)$

III. Results and Discussion

The energy required to dry 1 kg of maize grain from a moisture content of 25% to 13% wet basis was 1123.28 kJ/kg. In this study, 750 grams per hour of maize grain could be dried through simulation at an engine speed of 1000 rpm and a load of 18 Nm when biodiesel was used. In a related study, [7] dried 195 kg of rough rice in one batch in 14 hours using engine exhaust heat. [8] found 3150 kJ/kg as the energy requirements to dry 1 kg of rough rice from 23% to 15% moisture content on wet basis. Table 1 presents quantity of maize grain that could be dried with recovered energy from a moisture content of 25% to 13% wet basis.

Table 1: Dried Grain (g/h) for Different Engine Speeds and Torque Loads

Fuel	Speed	Torque Load				
		6 Nm	10 Nm	14 Nm	18 Nm	22 Nm
Diesel	1000 rpm	199.1569	276.6627	496.0994	580.5263	450.2404
	1250 rpm	264.1035	321.3844	376.6695	430.0274	254.2323
	1500 rpm	449.6316	534.4679	310.3972		
Biodiesel	1000 rpm	174.8910	283.6545	607.3159	749.7300	569.2904
	1250 rpm	351.4096	364.3970	604.7682	643.8415	191.1945
	1500 rpm	591.0057	585.4279	304.3353		

The result for amount of maize grain that could be dried with recovered energy when the engine was operated on diesel fuel at a speed of 1000 rpm show that it was 12.2% more than when the engine used biodiesel at a torque load of 6 Nm. When the torque load was increased to 10 Nm, quantity of maize grain that could be dried was 2.5% less for the engine fueled with diesel as compared to biodiesel fueling. Moreover, when the speed was maintained at 1000 rpm and the torque load increased at intervals of 4 Nm to 14 Nm, maize grain to be dried with recovered energy when the engine used diesel fuel was 22.4% less than when biodiesel was used. Subsequently, at a torque load of 18 Nm, 29.1% less could be dried when the engine used diesel as compared to biodiesel. However, at a torque load of 22 Nm, amount of maize grain to be dried resulted in a 26.4% decrease when the engine was operated on diesel in comparison to biodiesel. This is illustrated in Fig.1.

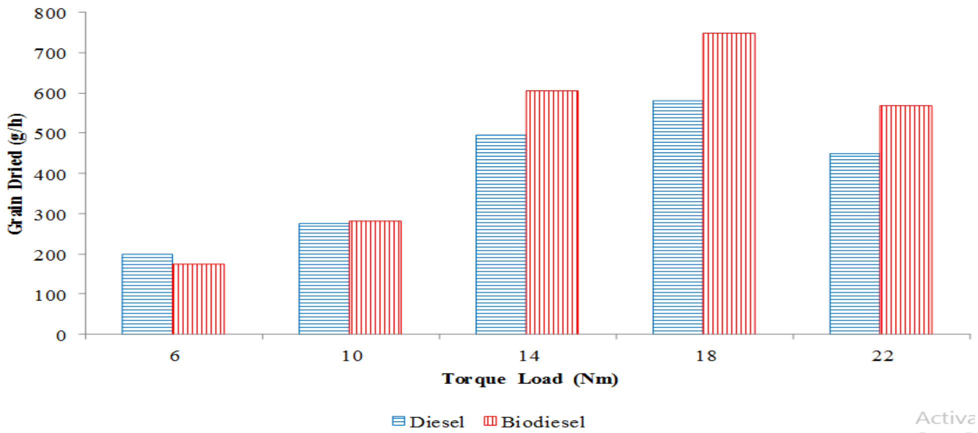

Figure 1: Estimated Grain Dried against Torque Load at 1000 rpm

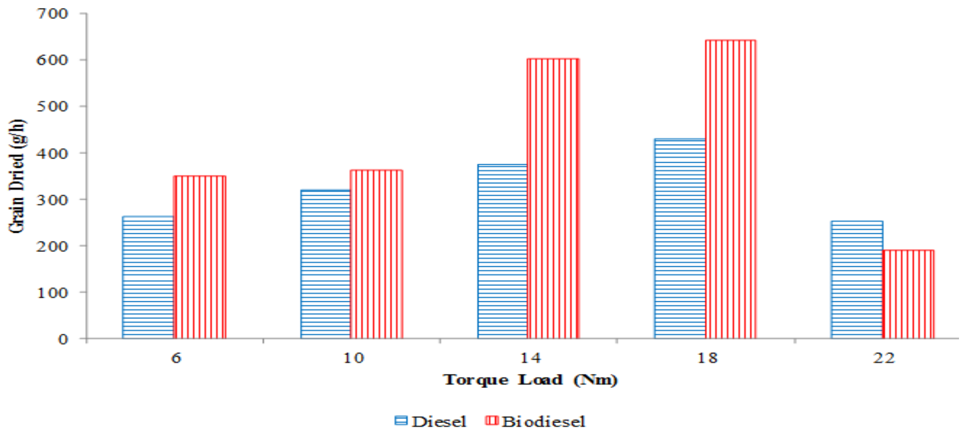

Figure 2: Estimated Grain Dried against Torque Load at 1250 rpm

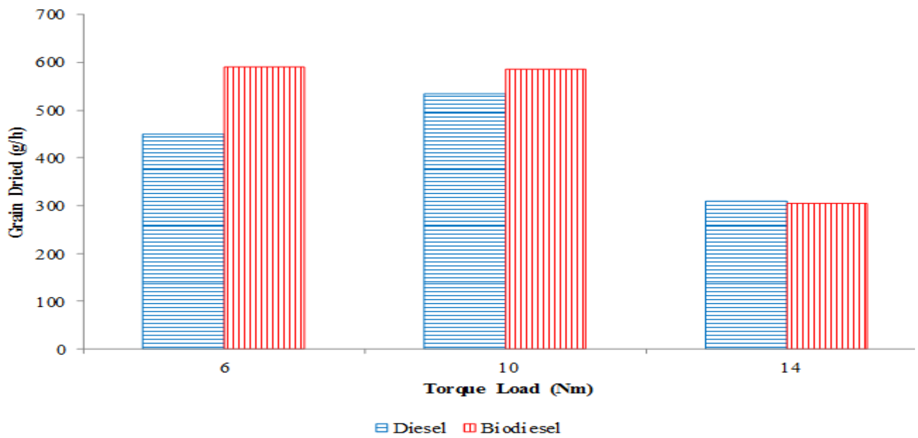

Figure 3: Estimated Grain Dried against Torque Load at 1500 rpm

As an application, increasing the engine speed to 1250 rpm gave the result of maize grain to be dried with recovered energy as 33.1% less when diesel fuel was used as compared to biodiesel at a torque load of 6 Nm. Moreover, the amount of maize grain that could be dried when the engine used diesel fuel was 13.4% less than when biodiesel was used at a torque load of 10 Nm. Similarly, at the engine speed of 1250 rpm and a torque load of 14 Nm, maize grain that could be dried when the engine used diesel fuel was 60.6% less than when biodiesel was utilized. However, when the torque load was increased to 18 Nm, maize grains to be dried with the recovered energy was 49.7% less and at 22 Nm, quantity of maize grain that could be dried was 24.8% more when the engine used diesel in comparison to biodiesel as presented in Fig. 2. Comparatively, when the engine was operated at a speed of 1500 rpm with a torque load of 6 Nm, maize grain that could be dried when the engine used diesel fuel was 31.4% less than when biodiesel was used. Subsequently, at a torque load of 10 Nm, quantity of maize grain that could be dried when the engine used diesel fuel was 9.5% less than when biodiesel was used. Similarly, at a torque load of 14 Nm, maize grains to be dried was 2% more when the engine used diesel as compared to biodiesel as shown in Fig. 3.

IV. Conclusions

This research was set out to recover exhaust gases energy from internal combustion engines for use in maize grain drying. The research used a 3.5 kW single cylinder, four-stroke, multi-fuel engine which was operated on diesel and biodiesel fuels. Many farmers have adopted mechanized agriculture and they use tractors in farms. Modern tractors have high engine capacities: Massey Ferguson 7170 model has an engine capacity of 170 hp (126.8 kW) and the John Deere 6165 J model has an engine capacity of 165 hp (123 kW). These capacities are about 35 times higher than the capacity of the engine used for this study. The specific conclusion drawn from the research is: through simulation, 1123.28 kJ/kg was determined as the energy required to dry 1kg of maize grain. With the recovered energy, about 600 grams per hour and 700 grams per hour of maize grain could be dried when the engine was operated on diesel and biodiesel respectively. Consequently, with modern tractors of engine capacities about 35 times higher than the one used in this research, 21-25 kg/h of maize grain could be dried.

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