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INJECTION SYSTEM ANALYSIS FOR A VARIABLE COMPRESSION ROTARY-PISTON ENGINE

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Abstract. The concern about the environment is highly increasing, and one of the main polluters are the conventional engines, that commonly have high emission taxes. As the legislation increase the taxes for the companies that have high emission vehicle, car manufacturers search for more efficient and less polluting engines occurs. The usual solution is generally the implementation of little incremental changes on current reciprocating four-stroke engines even though high production costs are required. Another way of reducing emissions is the use of biofuel. Nevertheless, as the conventional engines have a fixed compression ratio (CR) only one or two different fuel can be used on a single engine. A good solution for this problem is to develop new types of engines such as the Twin Rotor Piston Engine (TRPE). TRPE has variable compression ratio (VCR) which enables it to optimize the use of different fuels and mixtures. TRPE also optimizes the combustion conditions through all speed and load conditions. This paper presents estimated fuel combinations that the TRPE can use. As expected, while using ethanol or methanol fuel consumption is higher than when gasoline is used. Finally, the TRPE is a viable solution to reduce environment impacts because different fuels can be used at ideal conditions of combustion.

Keywords: internal combustion engines; rotary engines; fuel injection system.

1. INTRODUCTION

With the increasing of environmental damage, the countries have stated laws that limits pollution and environmental damage. As a result, car manufacturers started to innovate and research for new ways to reduce emissions. The industry developed different types of engines, like the oscillatory rotating engines, but it was gradually abandoned in the 1970s (Deng et al., 2013) due to the reliability of the old fashioned four-stroke reciprocating engine. With the lack of solutions to increase four-stroke engines efficiency, high production costs and complexity, twin rotor piston engines (TRPE) become an interesting choice of development. These engines have high power density, a smaller number of parts, lower maintenance costs, higher mechanical efficiency, and lower pollution compared to reciprocating engines (Deng et al., 2013, Zou et al., 2014).

Balki et al. (2014) measured the emissions and the efficiency of a four-stroke reciprocating engine using gasoline, ethanol and methanol at a fixed compression ratio. When emissions were studied, both methanol and ethanol performed better, except for the CO_2 emissions, where gasoline emitted less pollutant. When break thermal efficiency (BTE) was investigated, the best fuel in low RPM was methanol, while at higher RPM the ethanol had the higher BTE. The TRPE is known by its variable compression ratio (CR) that provides many advantages. It can vary the CR according to the fuel used and RPM, to achieve better efficiency, economy, or to emit less pollutant .The same engine can use a wide variety of fuels such as gasoline, ethanol, methanol, compressed natural gas, butanol, liquefied natural gas, and many others, that are not possible to use when the compression ratio does not change (Balki et al. 2014, Guarato et al., 2016b).

Moreover, at high engine loads and low speed, the TRPE can reduce the CR to prevent knock instead of retarding ignition time. It may increase the CR at high revolutions with a richer mixture to achieve better engine efficiency. The TRPE can also run on Miller cycle, providing a potential efficiency advantage compared to Otto cycle, at the cost of

engine power density (Ticona et al., 2015) and with thermodynamic simulation the Miller cycle showed 20% higher engine efficiency (Guarato et al., 2015).

With these wide range of fuels and two possible different operating cycles, a convenient ignition and fuel injection systems are necessary. This paper investigates the required conditions for the injection system to work within different conditions and with different fuels.

2. WORKING PRINCIPLE AND ENGINE CONFIGURATION

The TRPE has two rotors with an integrated pair of pistons at each of them (Guarato et al., 2016a). One pair of pistons move towards the other pair of pistons with a variable speed. Thus, some authors have named these engines as cat-and-mouse engines. In the first phase, intake air and fuel mixture go into the engine when one piston moves away from the other. Then mixture is compressed as the distance between pistons reduce and the ignition acts into the spark plug. The mixture ignites and the pistons move away from each in the combustion phase. Finally, the pistons come closer and the burnt gases are pushed out of the engine. This engine does not need any valves, which implies in a lower manufacturing cost compared to the common four-stroke reciprocating engine due to a lower number of components. Figure 1 presents TRPE and the two main sub-systems: the energy conversion system (ECS) and the differential velocity drive mechanism (DVDM).
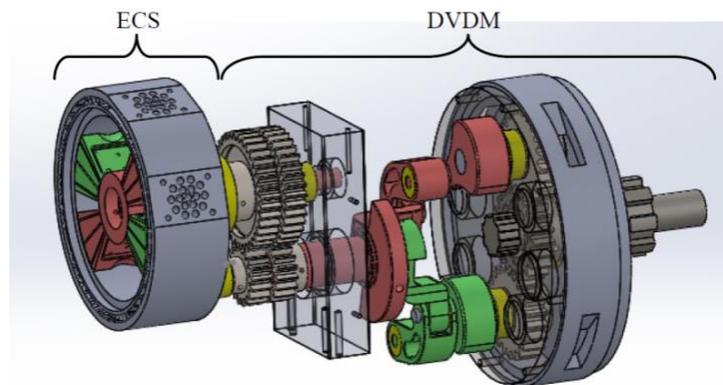

Figure 1. TRPE engine configuration. (Guarato et al., 2016b)

The engine conversion system (ECS) has a cylindrical housing, two cylindrical rotors, and one pair of pistons per rotor. The ECS is the sub-system in which the fuel combustion occurs. The combustion chamber is formed by the front face of one piston, the back face of lower face of the subsequent piston, the walls of the housing and the cylindrical surfaces of the rotors. Figure 2 shows assembly of pistons and rotors.
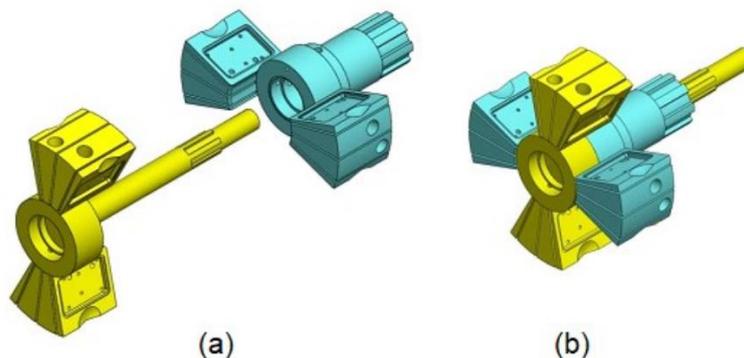

Figure 2: Rotors and pistons of a TRPE: (a) Exploded view, (b) Mounted in place (Oliveira, 2019).

The differential velocity drive mechanism DVDM is the sub-system that controls the variable speed of rotors. DVDM is composed by a stationary sun gear, two planetary gears and two crank-rocker mechanisms composed of planetary arms and connecting rods. The crank pins make an epicycloidal motion as the output shaft rotates. On the inflexion point of the epicycloidal curve one piston is as close as possible to the following piston. At this moment, the combustion process starts in one chamber and the exhaust process occurs in the opposite chamber (Figure 3). Detailed information about how TRPE works are present on previous work (Guarato et al., 2016b).
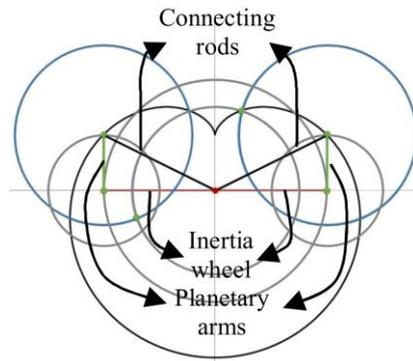
Figure 3: Epicycloidal motion of the DVDM (Guarato et al., 2016b).

3. ESTABLISHMENT OF EQUATIONS AND CONDITIONS

In the present work the following assumptions are made to validate the calculation. Thus, during calibration differences from the real scenario must be corrected by manipulating the values presented in this paper.

1. The mixture air fuel inside the engine is homogeneous;
2. The maximum Volumetric Efficiency (VE) the engine reach is 100%;
3. The RPM does not vary suddenly.

In order to calculate the amount of injected fuel into the engine, the mass of air that is inside de combustion chamber must be estimated. The mass of air that is supplied to the combustion chamber during the intake stroke is defined by the volumetric efficiency (VE). Table 1 presents a standard volumetric efficiency table. To build this table, it is supposed that the engine has maximum VE at a set RPM and the VE decreases as the load reduces. Posteriorly, the real Volumetric Efficiency of the engine must be measures for accurate results.

Table 1: Volumetric efficiency (VE) for TRPE.

VE Table [%]		RPM							
		350	700	1050	1400	1750	2100	2450	2800
	100	84,0	73,2	87,6	96,0	100,0	97,2	92,4	87,6
	90	57,6	69,6	84,0	92,4	94,8	93,6	88,8	84,0
	80	55,2	67,2	79,2	87,6	91,2	88,8	84,0	80,4
Load	65	50,4	62,4	73,2	81,6	84,0	82,8	79,2	75,6
[Kpa]	55	48,0	58,8	69,6	76,8	79,2	78,0	74,4	70,8
	45	45,6	55,2	66,0	72,0	75,6	73,2	69,6	66,0
	30	40,8	50,4	60,0	66,0	68,4	67,2	63,6	60,0
	20	38,4	46,8	56,4	61,2	63,6	62,4	58,8	56,4

$$VE = m_{air\ supplied}/(\rho_{atmospheric} * V_{cylinder}) \tag{1}$$

Table 2 is built using Eq. (1) and it shows the amount of air that passes trough the intake valve in each condition. In the table cells, the mass of air inside the cylinder is displayed.

After the mass of air inside the cylinder is defined, the amount of fuel that is injected into the combustion chamber is calculated. Eq. (2) defines the air fuel ratio (AFR) as the mass of air per each mass of fuel. Table 3 shows the limits of AFR considering a lean and a rich mixture for the gasoline, ethanol and methanol. According to Blair (1999), if the mixture becomes too lean the flame is prevented to grow because the mass of fuel that is ignited is too small to release the adequate heat necessary to ignite the surrounding mixture. Also, if the mixture is too rich the flame is prevented from growing because there is not enough mass of air around the spark. The lean mixture is considered when lambda is between 1 and 1,20 and the rich mixture is when the lambda is between 1 and 0,8. Lambda is the ratio between the AFR and the stoichiometric AFR. The values presented in Table 3 are the air fuel ratio in most of the situations, but in some cases the engine may run outside these parameters.

Table 2: Air mass supplied to the cylinder.

Air mass [kg]		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	0,0004911	0,0004279	0,0005121	0,0005612	0,0005846	0,0005682	0,0005402	0,0005121
	90	0,0003367	0,0004069	0,0004911	0,0005402	0,0005542	0,0005472	0,0005191	0,0004911
	80	0,0003227	0,0003929	0,000463	0,0005121	0,0005332	0,0005191	0,0004911	0,00047
	65	0,0002946	0,0003648	0,0004279	0,000477	0,0004911	0,0004841	0,000463	0,000442
	55	0,0002806	0,0003438	0,0004069	0,000449	0,000463	0,000456	0,000435	0,0004139
	45	0,0002666	0,0003227	0,0003858	0,0004209	0,000442	0,0004279	0,0004069	0,0003858
	30	0,0002385	0,0002946	0,0003508	0,0003858	0,0003999	0,0003929	0,0003718	0,0003508
	20	0,0002245	0,0002736	0,0003297	0,0003578	0,0003718	0,0003648	0,0003438	0,0003297

$$AFR = m_{air}/m_{fuel} \qquad (2)$$

Table 3: Adequate air fuel ratios (AFR) for ethanol, methanol and gasoline (Heywood, 2018).

AFR	Lean	Stoich	Rich
Gasoline	17,6	14,7	11,8
Ethanol	10,8	9,0	7,2
Methanol	7,8	6,5	5,2

Considering the limits in Table 3, Table 4, Table 5 and Table 6 are built, which shows inside the cells the air fuel ratio for different operating conditions. When maximum output power is required, the engine runs at wide open throttle and with a richer mixture to provide more output energy. This situation is shown in the upper side of these tables. At low loads, a leaner mixture is used to provide better fuel economy. This situation is shown in the lower part of these tables.

Table 4: AFR for gasoline at different operating conditions.

Gasoline AFR table		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5
	90	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5
	80	12,5	12,5	12,5	12,5	12,5	12,5	12,5	12,5
	65	14,0	14,0	14,0	14,0	14,0	14,0	13,2	13,2
	55	15,4	15,4	15,4	15,4	15,4	15,4	14,7	14,7
	45	16,2	16,2	16,2	16,2	16,2	16,2	14,7	14,7
	30	16,2	16,2	16,2	16,2	16,2	16,2	14,7	14,7
	20	16,2	16,2	16,2	16,2	16,2	16,2	14,7	14,7

Table 5: AFR for ethanol at different operating conditions.

Ethanol AFR table		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	7,7	7,7	7,7	7,7	7,7	7,7	7,7	7,7
	90	7,7	7,7	7,7	7,7	7,7	7,7	7,7	7,7
	80	7,7	7,7	7,7	7,7	7,7	7,7	7,7	7,7
	65	8,6	8,6	8,6	8,6	8,6	8,6	8,1	8,1
	55	9,5	9,5	9,5	9,5	9,5	9,5	9,0	9,0
	45	9,9	9,9	9,9	9,9	9,9	9,9	9,0	9,0
	30	9,9	9,9	9,9	9,9	9,9	9,9	9,0	9,0
	20	9,9	9,9	9,9	9,9	9,9	9,9	9,0	9,0

Table 6: AFR for methanol at different operating conditions.

Methanol AFR table		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	5,5	5,5	5,5	5,5	5,5	5,5	5,5	5,5
	90	5,5	5,5	5,5	5,5	5,5	5,5	5,5	5,5
	80	5,5	5,5	5,5	5,5	5,5	5,5	5,5	5,5
	65	6,1	6,1	6,1	6,1	6,1	6,1	5,8	5,8
	55	6,8	6,8	6,8	6,8	6,8	6,8	6,5	6,5
	45	7,1	7,1	7,1	7,1	7,1	7,1	6,5	6,5
	30	7,1	7,1	7,1	7,1	7,1	7,1	6,5	6,5
	20	7,1	7,1	7,1	7,1	7,1	7,1	6,5	6,5

4. DISCUSSION AND RESULTS

The combination of all previous tables results in Table 7, Table 8 and

Table **9**, that shows the mass of fuel that is injected in the cylinder in each operating condition of the engine with different fuels. These tables must be implemented in an injection system. This injection system interpolates the table values to reach the exact fuel amount to inject inside the cylinder.

Table 7: Mass of gasoline injected inside the cylinder per cycle.

Gasoline mass [kg]		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	3,9286E-05	3,4235E-05	4,0970E-05	4,4899E-05	4,6769E-05	4,5460E-05	4,3215E-05	4,0970E-05
	90	2,6939E-05	3,2552E-05	3,9286E-05	4,3215E-05	4,4337E-05	4,3776E-05	4,1531E-05	3,9286E-05
	80	2,5817E-05	3,1429E-05	3,7041E-05	4,0970E-05	4,2654E-05	4,1531E-05	3,9286E-05	3,7603E-05
	65	2,1046E-05	2,6057E-05	3,0567E-05	3,4075E-05	3,5077E-05	3,4576E-05	3,5077E-05	3,3483E-05
	55	1,8222E-05	2,2322E-05	2,6422E-05	2,9155E-05	3,0066E-05	2,9610E-05	2,9589E-05	2,8157E-05
	45	1,6456E-05	1,9920E-05	2,3818E-05	2,5983E-05	2,7282E-05	2,6416E-05	2,7680E-05	2,6248E-05
	30	1,4724E-05	1,8188E-05	2,1653E-05	2,3818E-05	2,4684E-05	2,4251E-05	2,5294E-05	2,3862E-05
	20	1,3858E-05	1,6889E-05	2,0353E-05	2,2086E-05	2,2952E-05	2,2519E-05	2,3385E-05	2,2430E-05

Table 8: Mass of ethanol injected inside the cylinder per cycle.

Ethanol mass [kg]		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	6,3776E-05	5,5577E-05	6,6510E-05	7,2887E-05	7,5924E-05	7,3798E-05	7,0154E-05	6,6510E-05
	90	4,3732E-05	5,2843E-05	6,3776E-05	7,0154E-05	7,1976E-05	7,1065E-05	6,7421E-05	6,3776E-05
	80	4,1910E-05	5,1021E-05	6,0132E-05	6,6510E-05	6,9243E-05	6,7421E-05	6,3776E-05	6,1043E-05
	65	3,4261E-05	4,2419E-05	4,9760E-05	5,5471E-05	5,7102E-05	5,6286E-05	5,7163E-05	5,4564E-05
	55	2,9539E-05	3,6185E-05	4,2831E-05	4,7262E-05	4,8739E-05	4,8000E-05	4,8328E-05	4,5990E-05
	45	2,6928E-05	3,2597E-05	3,8975E-05	4,2518E-05	4,4644E-05	4,3226E-05	4,5210E-05	4,2872E-05
	30	2,4093E-05	2,9762E-05	3,5431E-05	3,8975E-05	4,0392E-05	3,9683E-05	4,1313E-05	3,8975E-05
	20	2,2676E-05	2,7636E-05	3,3305E-05	3,6140E-05	3,7557E-05	3,6849E-05	3,8195E-05	3,6636E-05

Table 9: Mass of methanol injected inside the cylinder per cycle.

Methanol mass [kg]		RPM							
		350	700	1050	1400	1750	2100	2450	2800
Load [Kpa]	100	8,9287E-05	7,7807E-05	9,3114E-05	1,0204E-04	1,0629E-04	1,0332E-04	9,8216E-05	9,3114E-05
	90	6,1225E-05	7,3981E-05	8,9287E-05	9,8216E-05	1,0077E-04	9,9491E-05	9,4389E-05	8,9287E-05
	80	5,8674E-05	7,1430E-05	8,4185E-05	9,3114E-05	9,6940E-05	9,4389E-05	8,9287E-05	8,5460E-05
	65	4,8303E-05	5,9803E-05	7,0154E-05	7,8205E-05	8,0505E-05	7,9355E-05	7,9831E-05	7,6202E-05
	55	4,1267E-05	5,0552E-05	5,9837E-05	6,6027E-05	6,8091E-05	6,7059E-05	6,6916E-05	6,3678E-05
	45	3,7547E-05	4,5452E-05	5,4345E-05	5,9285E-05	6,2249E-05	6,0273E-05	6,2599E-05	5,9361E-05
	30	3,3595E-05	4,1500E-05	4,9404E-05	5,4345E-05	5,6321E-05	5,5333E-05	5,7203E-05	5,3965E-05
	20	3,1619E-05	3,8535E-05	4,6440E-05	5,0392E-05	5,2369E-05	5,1380E-05	5,2885E-05	5,0727E-05

Some important observations can be highlighted:

1. The bigger fuel consumption is when the engine is operating with methanol as it is expected, since the methanol has the lower AFR for the stoichiometric mixture. The advantage of the TRPE is that when it operates with leaner mixtures, instead of retarding ignition advance to avoid detonation, it can lower its compression ratio. This has an impact on the efficiency and can also reduce the emissions.

2. In this article, the calculations are carried out based on a standard volumetric efficiency table. For more precise results, it is necessary to run the engine and measure the volumetric efficiency for each condition. Also, for the same load, the volumetric efficiency changes for the different speeds of the engine. This happens due to the air flow in the intake which varies with the piston speed. Each engine has its own characteristics and to obtain the exact VE, it must run an experiment (Heywood, 2018).

3. The exact limits of the lean and rich mixtures that an engine may run depends of the ignition timing and the header and piston design. Although, for these calculations it is convenient to consider this general table. Also, the AFR table varies with the demands. It depends of the calibration and the requisites of the project. If the maximum output power is required, a richer mixture must be used. If economy is desired, a leaner mixture must be used

4. A homogeneous mixture is considered because when it is heterogeneous, there is no precision of how much richer the mixture must be

5. When the engine runs with a turbocharger, the Volumetric Efficiency exceeds 100% and other considerations should be done

6. When the load suddenly increases, the engine must run with the AFR 2 or 3 times lower than with stoichiometric mixture.

7. All these results must be refined by making an experiment measuring the real volumetric efficiency.

The fuel injected inside the cylinder is proportional to the volumetric efficiency in each situation. As expected, at low loads there is less fuel being injected into the engine because of the lower VE. Also, at low loads, a leaner mixture is used to provide better fuel economy, which reduces even more the fuel consumed.

When analyzing high loads, the fuel injected is up to 2 times the fuel injected at low loads. The main reason for that is the volumetric efficiency, that is higher when the engine runs at wide open throttle. Moreover, the mixture is richer to improve power output, which causes a higher fuel consumption.

At the same RPM, the fuel injected inside the cylinder varies mainly because the VE is not constant through the entire range of speed the engine works. In higher loads, it is used the same AFR at all engine speeds to provide more output power. But at mid and low loads, the air fuel ratio varies according to the engine speed. At lower speeds, a leaner mixture is used to provide better fuel economy, while at high speeds a lower AFR is used to provide more power output.

In the conditions analyzed, the gasoline is always the less consumed fuel when comparing to ethanol and methanol at the same load and RPM. That is because the gasoline has the bigger lower calorific value of the fuels analyzed, so it must burn a less amount of fuel to generate the same power of the other fuels. Also, when the engine runs with methanol, it consumes more fuel than ethanol.

5. CONCLUSIONS

The twin rotor piston engine (TRPE) is a versatile engine as it may use different fuels or mixtures while setting the ideal compression ratio (CR). It may fit the best emission and consumption requirements when necessary, but it also may raise the CR in order to produce more output power.

Its noticeable that the TRPE can reduce significantly the environmental damage caused by internal combustion engines. It also greatly expands the possibilities of using different available fuels in the same engine. With a proper fuel injection calibration and the variable compression ratio (VCR) system, TRPE may have a greater thermal efficiency and lower emissions than current reciprocating engines regardless the type of fuel or mixture that is used. Due to the lack of valves, TRPE has a lower coefficient of discharge, improving the power output in high speed with full loads. Moreover, when compared to conventional engines TRPE is simpler to manufacture, more compact and it has a higher power to weight ratio. Therefore, TRPE is a viable substitute to convention engines. Future works will focus on the cost of implementation of this new engine into the market.

These results suit as a basis to start the calibration process of a TRPE engine with different types of fuel. When running with gasoline, the injection system must inject less fuel inside the combustion chamber of the engine. While running with ethanol or methanol the fuel consumption is higher than with gasoline. Also, at higher loads and higher engine speeds, TRPE may run a richer mixture to provide more power output. At lower loads and RPM, the engine runs leaner to have a better fuel economy, as expected.

6. ACKNOWLEDGEMENTS

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