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Experimental Investigation of the Effect of Injection of Oxy-Hydrogen Gas on the Speed Characteristics of Diesel Engine

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ABSTRAC: *Oxy-Hydrogen gas, H_2O_2, is a mixture of hydrogen and oxygen produced by water electrolysis. In this work, an experimental exploration was carried out in order to study the effect of the addition of oxy-hydrogen gas into inlet air manifold on speed performance characteristics of a diesel engine at different operating conditions. The experimental work was performed on a test rig comprising a four stroke 5.67 liters water-cooled diesel engine and a Heenan hydraulic dynamometer. Instrumentation included devices for measuring engine speed, load, fuel consumption and inlet air flow rate. The measurements were conducted at 1000, 1500, 2000 and 2500 rpm. At each speed, the engine load was adjusted to 20%, 40% and 80% from the engine full load which corresponds to engine brake mean effective pressures of 1.55, 3.11, and 6.22 bar, respectively, for Oxy-hydrogen generator supplied Currents of 26A and electrolyte concentration of 25 %.*
The fuel saving percentage and so the brake thermal efficiency for the H_2O_2 enriched CI engine is more evidently seen at low loads and high-speed conditions. the volumetric efficiency drop was about 5 % at small speeds and reaches to about 2% at higher engine speed.
Keywords *diesel engine- speed characteristics- Oxy-Hydrogen addition*

I. INTRODUCTION

Due to the depletion of fossil fuels and ever increasing oil prices, engine manufacturers worldwide are currently encouraged to find out alternative approaches to increase fuel economy and reduce harmful emissions from internal combustion engines. One of the possible ways to increase the performance of diesel engines is to use an additive as complementary fuel along with diesel, leading to reduced fuel consumption and toxic gas emissions. Researchers worldwide have investigated the effect of adding several additives to diesel fuel on the performance of diesel engines [1–3].

Compared to diesel, hydrogen has wider flammability limits, higher flame speed and faster burning velocity [4] which enable engines running on very lean mixtures [5–7]. Unlike other additives, hydrogen is a renewable and clean-burning fuel [8–10] and the addition of hydrogen to hydrocarbon-based fuels does not increase any threat in increasing the toxic gas emissions. Moreover, generation of hydrogen is possible from a variety of sources such as fossil fuels, biomass, water and some industrial waste chemicals [11,12]. Due to the unique combustion nature of hydrogen, the addition of hydrogen to the fuels with a low level of burning rate can improve the combustion rate of the formed mixture [9].

To store hydrogen onboard in forms of a compressed gas, a cryogenic liquid or a gas dissolved in metal hydrides, a large amount of hydrogen is required to be stored and carried which leads to increase in the overall weight of the vehicle [13]. Alternatively, in terms of liquid hydrogen storage, not only the cost of onboard cryogenic containers is high, but also a high level of energy is required to convert the gaseous hydrogen into liquid [14]. Therefore, the use of small and light hydrogen containers are respected which need to be filled in short distances of driving. However, hydrogen supply infrastructures are not still available and need to be developed in the near future [15,16]. In addition, the wide flammability range of hydrogen makes it a hazardous fuel to be stored which can be combusted at atmospheric pressure at concentrations from 4% to 74.2% by volume [17].One of the viable solutions to this problem is to generate hydrogen aboard through electrolysis of water and use it in the form of hydrogen–oxygen (H2/O2) mixture. However, no significant work has been carried out in a testing diesel engine with the addition of H_2/O_2 mixture.

Few researches have been done on this concept. Some of these works were conducted to improve the thermal efficiency of petrol engines such as Amman A. [18], A.M.Falhat, et al. [19], Tuan Le Anh, et al. [20] and EL-Kassaby et al. [21].

Some others worked to enhance the performance of diesel engines. Bari and Esmaeil [22] performed experimentations on four-cylinder direct injection diesel engine. The experiments were carried out under the constant speed of 1500 rpm with three different power level. The result showed that with the introduction of H_2O_2 gas at different percentage into a diesel engine, the brake thermal efficiency increased by the increase of engine load. The brake specific fuel consumption of engine was reduced as the engine load increased. It was also noticed that adding H_2O_2 beyond 5% does not have a significant effect on engine performance. The emissions HC, CO, and CO2 were found to be reduced while NOx increases due to higher temperature achieved during the combustion process.

Ali Can Yilmaz, et al. [23] produced H_2O_2 gas with different electrolytes KOH (aq.), NaOH (aq), NaCl (aq) with various electrode design in a leak proof plexiglass reactor. The engine used was four cylinder, four stroke compression ignition engine. Results showed that there was 19.1% increment in engine torque when the H_2O_2 system was used compared to diesel operation whereas 14% gain was achieved on specific fuel consumption using Oxy-Hydrogen gas. Also about 13.5% reduction in CO emission and 5% reduction in HC but experiment showed that at low engine speed with constant H_2O_2 flow rate turned into disadvantage for torque ,CO, HC, and SFC this is because of long opening time of intake manifold at low speed which causes excessive volume occupation of H_2O_2 in cylinder which prevents correct air to be taken into combustion chamber due which volumetric efficiency decreases that influenced combustion efficiency which had adverse effect on performance parameter. Dahake et al. [24] carried out some experimentations on single cylinder four stroke diesel engine, it was seen that the oxy-hydrogen gas enrichment resulted in significant improvement in performance and reduction in emission parameters except the exhaust gas temperature and NO emission which increases with increase in load. The thermal efficiency of the diesel engine was found to increase when enriched with oxy-hydrogen gas. The aim of this study is to investigate the effect of adding H_2O_2 gas on the speed performance characteristics of a diesel engine at variable loads of 1.55, 3.11 and 6.22 BMEP. The engine was tested at different speeds of 1000.1500, 2000 and 2500 rpm with the addition of a constant amount of H_2O_2 gas (1.3 Nl/min), corresponding to the oxy-hydrogen generator supplied current of 26 A with electrolyte concentration of 25 %.

II. EXPERIMENTAL WORK

2.1 Experimental Setup

The experimental work was conducted on a complete rig (available in the laboratory of mechanical power and energy at the Military Technical College) for testing naturally aspirated as well as turbocharged diesel engines. The test rig includes the engine and all the instrumentation necessary for measuring and recording the operating parameters. An on-line data acquisition system is furnished to improve the speed and accuracy of data collection and recording. A transport diesel engine of type Mercedes-Benz with an open chamber is used. This is a four stroke 6-cylinder with 97 mm bore, 128 mm stroke, and 17: 1 compression ratio. Detailed engine specifications are given in appendix (A).

Engine external loading was carried out by an ELZE /Heenan hydraulic dynamometer. The fluid used was water with which the maximum braking power could reach 170 kW at 4000 rpm. The engine and dynamometer shafts were directly coupled through a Cardan shaft.

The test rig is fully instrumented in order to acquire experimental data as well as to monitor the engine operating conditions. Figure1 gives a general scheme of the complete test rig showing numbered locations where important pickups and transducers concerning our experimental work are positioned. a list of these locations and the corresponding measured parameter at each is given Table 1.The engine speed is measured using shaft encoder. Also, it was measured and monitored frequently using a hand held digital tachometer model Lutron DT-2234. The diesel fuel consumption was calculated by measuring the time required to consume a fixed volume of fuel and using the following equation.

$$\dot{m}_f = \frac{V_f \rho_f}{t} \quad (1)$$

A standard orifice of 60 mm diameter is mounted at the air surge tank entrance with a U-tube manometer which is fitted downstream the settling chamber to measure the air pressure drop across the orifice as shown in figure 1. The air flow rate is calculated from the orifice area and the manometer reading.

$$\dot{m}_{air} = C_d A_{orifice} \sqrt{\frac{2\Delta p}{\rho_{air}}} \qquad (2)$$

A thermocouples type K (NiCr-Ni), which is connected to a digital readout is used to measure the temperature of the exhaust manifold
The mixture of H_2O_2 was generated by electrolyzing water using an oxy-hydrogen generator specially designed and manufacturing. The characteristics of the generator are measured as shown in figure 2. In order to simplify the setup, the H_2/O_2 mixture was generated using 12 V external power supply. But in reality, it will be produced from the battery/alternator arrangement of the engine. The power needed to produce the H_2/O_2 mixture is included as an input energy to the engine. The generated mixture is then passed through a drier container before it is introduced to the engine via the air inlet manifold. A flame arrestors were installed into the H_2/O_2 line for suppressing explosions anywhere in the line. The supplied current is measured by clamp ampere (Lutron CM-9940)

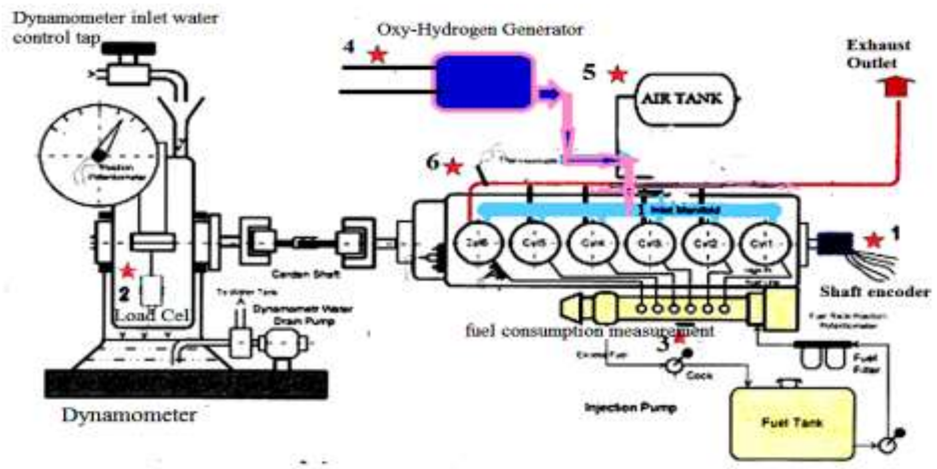

Figure 1: Schematic of test rig;*i point of measurements of the ith parameter

Table 1: List of measuring locations and the parameter measured at each (Relevant to Figure 1)

Location	Measured Parameter	Measuring device
1	Engine speed	Shaft encoder / digital tachometer model Lutron DT-2234
2	Brake torque	ELZE /Heenan hydraulic dynamometer
3	Fuel consumption	Recording the consumption time of fixed
4	HOH generator supplied current	clamp ampere (Lutron CM-9940)
5	The air pressure drop across the	U-tube manometer

2.2 Test procedure

Measured parameters included engine speed, engine power (calculated from the dynamometer reading), fuel consumption and inducted air mass flow rate. The tests were conducted on the diesel engine with and without introducing the oxy-hydrogen gas. One oxy-hydrogen generator was used in these tests whose characteristics are given in figure 2 and its specifications were given in Appendix B. The measurements were carried out at 1000, 1500, 2000 and 2500 rpm. At each speed, the engine load was adjusted to 20%, 40% and 80% from the engine full load which corresponds to 1.55, 3.11, and 6.22 brake mean effective pressure for Oxy-hydrogen generator supplied Currents of 26 A and electrolyte concentration of 25 %.

Table 2 list the experiments carried out at different engine operating conditions. Measured values are to the table left, while related calculated overall parameters are to the right. The engine conventional characteristics that were drawn from the experimentally obtained data are briefly presented in the following sections

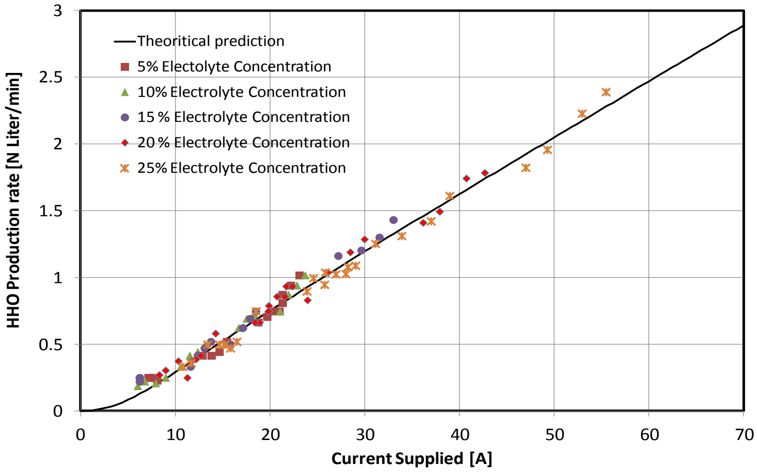

Figure 2: H_2O_2 production rate of the oxy-hydrogen generator used in this work [25]

Table 2: Summary of carried out experiments

No.	Measured parameters	Engine Speed	% of load to engine full load	Generator Operating	Calculated engine parameters
1	• the electrical load current • electrical load voltage • Fuel consumption • Inducted air mass flow rate	1000	20% 1.55 bar	Supplied Current = 26 A Electrolyte Concentration = 25%	• Engine power • Brake specific fuel consumption • Fuel saving percentage • effective thermal efficiency • Excess air factor • Volumetric efficiency
2		1500			
3		2000			
4		2500			
5		1000	40 % 3.11 bar		
6		1500			
7		2000			
8		2500			
13		1000	80% 6.22 bar		
14		1500			
15		2000			
16		2500			

III RESULTS AND DISCUSSIONS

3.1 Brake Specific Fuel Consumption

The brake specific fuel consumption is inversely proportional to the engine indicated efficiency and engine mechanical efficiency by the equation

$$g_e = \frac{3600}{\eta_e H_l} \quad (3)$$

$$g_e = \frac{3600}{\eta_i \eta_m H_l} \quad (4)$$

where

g_e is the specific fuel consumption [gm/kW.hr]

η_e is the effective thermal efficiency

η_i is the indicated thermal efficiency

η_m is the mechanical efficiency

H_l is the lower heating value of the fuel [MJ/kg]

Figure3 shows a comparison between the brake specific fuel consumption between the diesel engine with and without introducing H_2O_2 gas at three loads namely 1.55, 3.11 and 6.22 Brake mean effective pressure for different speeds.

The fuel saving percentage for the H_2O_2 enriched CI engine is more evidently seen at low loads and high-speed conditions as shown in figure 4. The reduction in SFC is due to uniform mixing of H_2O_2 with air (high diffusivity of H_2O_2) as well as oxygen index of H_2O_2 gas which assists fuel during the combustion process and yields better combustion. This can be attributed to that, at high speeds, the diesel fuel is hard to be completely burnt at lean conditions due to the increased residual gas fraction and poor mixing. Since H_2O_2 gains a high flame speed and wide flammability, the addition of hydrogen would help the fuel to be burned faster and more complete at high-speed conditions. Also, low ignition energy of H_2O_2-air mixture derives diesel fuel even to be burned safely under leaner conditions. However, at low speeds (≤1500 rpm), low lean flammability limit constraints H_2O_2 to have a better positive influence on combustion efficiency due to mixture requirement around stoichiometric conditions.

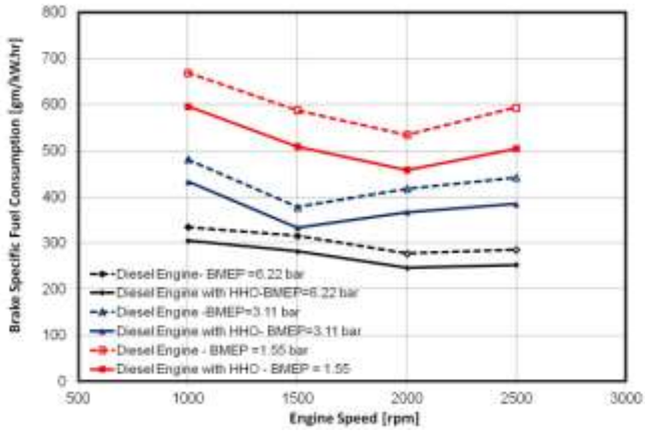

Figure 3: A comparison between the brake specific fuel consumption between the diesel engine with and without introducing H_2O_2 gas

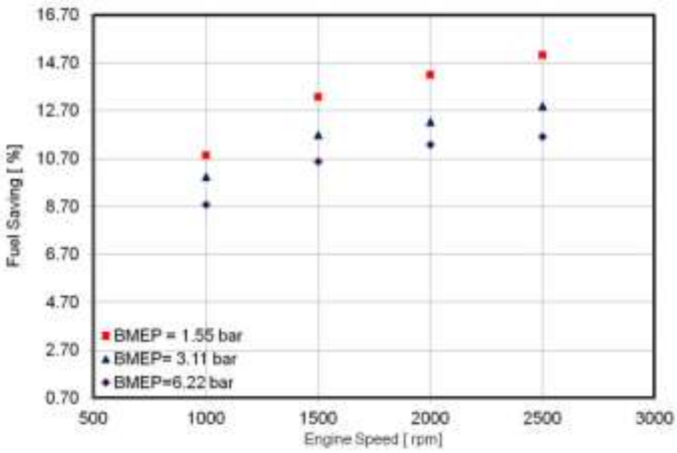

Figure 4: Fuel saving percentage for the H_2O_2 enriched CI engine at different engine loads

3.2 Brake thermal efficiency

Figure 5 shows a comparison between the brake thermal efficiency of the diesel engine with and without introducing H_2O_2 gas at three loads namely 1.55, 3.11 and 6.22 Brake mean effective pressure for different speeds.

Brake thermal efficiency is usually used to symbolize the engine economic performance. The improvement in engine brake thermal efficiency for the H_2O_2 enriched CI engine is more evidently seen under high-speed conditions. The brake thermal efficiency is inversely proportional to the brake specific fuel consumption so increasing the thermal efficiency can be attributed to the same reasons discussed for decreasing the specific fuel consumption.

3.3 Excess Air Factor

The Excess air factor is shown to decrease at lower speeds due to the decreases of amount of air inducted by the engine cylinder and decreases also at higher speeds due to the increase of fuel consumption

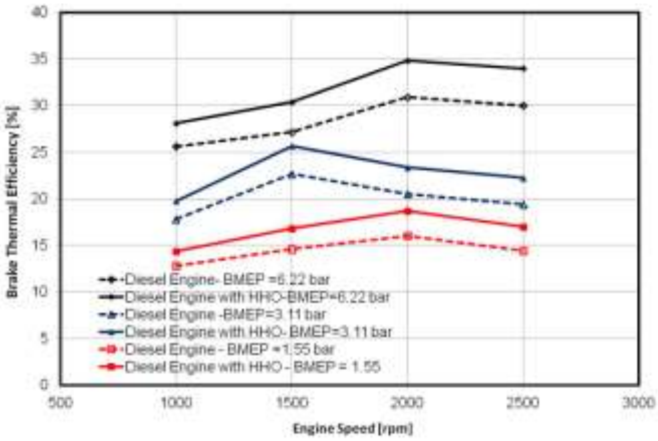

Figure 5: A comparison between the brake specific fuel consumption between the diesel engine with and without introducing H_2O_2 gas

As the H_2O_2 gas is inducted through the intake air the gas replaces some air that could result in reduced air–fuel ratio. Instead, figure 6 shows that the air–fuel ratio increases with increasing H_2O_2 gas. This is due to the fact that the inducted mixture contains oxygen and hydrogen as well. This increase in air–fuel ratio improves the combustion resulting lower fuel consumption and better efficiency H_2O_2The increases in excess air factor were from 2.5 at 1000 rpm and BMEP of 1.55 when running with pure fuel to 2.75 when H_2O_2 gas is introduced, and from 2.39 to 2.81 at 2500 rpm at the same load. At a higher load of 6.22 BMEP, The increases in excess air factor were from 1.21 to 1.26 at 1000 rpm when H_2O_2 gas is introduced and from 1.2 to 1.33 at 2500.

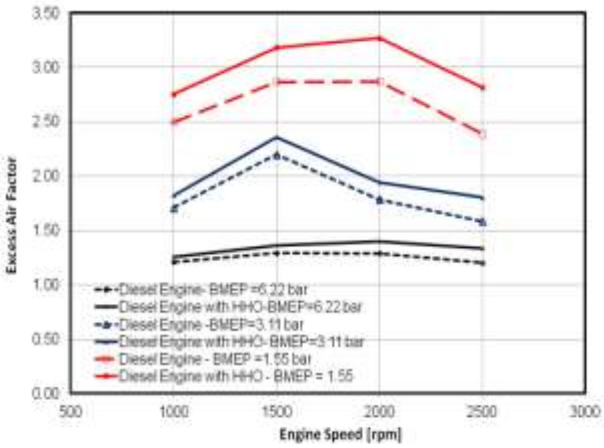

Figure 6: A comparison between the excess air factor between the diesel engine with and without introducing H_2O_2 gas

3.4 Volumetric Efficiency

The volumetric efficiency is shown to decrease with engine speed at all loads. This can be attributed to that as the engine speed increases less time available for cylinder filling and scavenging so the residual gas coefficient increases. As the engine load increases the engine preheating temperature for the fresh charge increases so the fresh charge density decreases causing a slight drop in volumetric efficiency. As H_2O_2 gas is inducted to the engine cylinder it replaces some of the air sucked by the movement of pistons so it is predicted that the volumetric efficiency decreases as shown in figure 7. It is shown that the volumetric efficiency drop was about 5 % at small speeds and reaches to about 2% at high speeds due to higher H_2O_2 gas flow share at low engine speeds and lower H_2O_2 gas flow share at high engine speed. The flow rate of H_2O_2 gas remain constant at all engine speeds as the generator current and electrolyte concentration remain unchanged while the volume flow rate needed to fill the engine increases as engine speed increases so

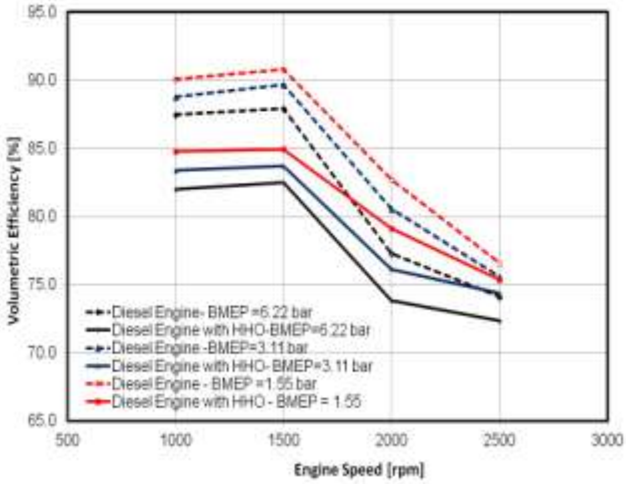

Figure 7: A comparison between the volumetric efficiency between the diesel engine with and without introducing H_2O_2 gas

IV. CONCLUSIONS

The effect of using a small amount of H_2O_2 mixture as an additive on the speed performance characteristics of a four-cylinder diesel engine was evaluated. Hydrogen has about nine times higher flame speed than diesel so it has the ability to enhance overall combustion characteristics, generating higher peak pressure closer to TDC resulting in more work. Specific Conclusions can be summarized as:

- The fuel saving percentage and so the brake thermal efficiency for the H_2O_2 enriched CI engine is more evidently seen at low loads and high-speed conditions. due to the difficulties of complete pure fuel burning at high speeds, due to the increased residual gas fraction and poor mixing. Since H_2O_2 gains a high flame speed and wide flammability, the addition of hydrogen would help the fuel to be burned faster and more complete at high-speed conditions.
- the volumetric efficiency drop was about 5 % at small speeds and reaches to about 2% at high speeds due to higher H_2O_2 gas flow share at low engine speeds and lower H_2O_2 gas flow share at high engine speed.
- The increases in excess air factor were from 2.5 at 1000 rpm and BMEP of 1.55 when running with pure fuel to 2.75 when H_2O_2 gas is introduced, and from 2.39 to 2.81 at 2500 rpm at the same load. At a higher load of 6.22 BMEP, The increases in excess air factor were from 1.21 to 1.26 at 1000 rpm when H_2O_2 gas is introduced and from 1.2 to 1.33 at 2500.

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Appendix A Engine Technical Data

Make and Model	Mercedes 352 series -Natural aspirated Diesel engine
Compression ratio	17 : 1
No. of Strokes	4
No. of cylinder	6
Arranging	In-line
Cooling	Water
Bore	97 mm
Stroke	28 mm
Combustion chamber	Open type, Direct Injection
Cam shaft	Sided
Speed range	800-2800 rpm
Maximum power	120 HP at 2800 rpm
Maximum torque	28 kp.m at 1600 rpm
Static injection	23 CA BTDC
Firing order	1 5 3 6 2 4 1
Min. compression pressure	20 bar at 150-200 rpm
Injector opening pressure	200 bar

Appendix B Oxy-Hydrogen Generator Technical Data

Design	leak proof plexiglass reactor
Electrodes	stainless chromium-nickel steel plates 316L
Number of cells	18
Connections	Three (6 cells in series) in parallel
Electrode area	[13 cm X8 cm]
Electrode spacing	2 mm
Electrolyte Concentration	KOH (5-25%)
Maximum Current intensity	1500 A/m^2
Operating Voltage	12 Volt
Maximum Operating Temperature	80 ^oC

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