This invention is concerned with improvements in or relating to free-piston internal combustion engines.

It is well-known that in internal combustion piston-and-cylinder engines during every cycle of operation of the engine a quantity of fuel is consumed which corresponds to the quantity of oxygen from the air compressed in a cylinder, the gas temperatures in general reaching values higher than 2 000°K within the cylinder.

It would be preferable to reduce the richness in hydrocarbons (i.e. the ratio of the quantity of oxygen in the air within a cylinder which is capable of participating in the combustion to the quantity of oxygen which would be consumed by complete combustion of the fuel introduced into the cylinder, which usually varies, at maximum load of the engine, from 0.4 for a diesel engine with a high air excess, to 1.2 for an Otto cycle engine. Actually, high richness of the fuel-air mixture tends to cause emission into the atmosphere of three poisonous products:

(i) the unburnt products resulting from incomplete combustion of hydrocarbons,

(ii) carbon monoxide resulting from combustion in the presence of an insufficient quantity of oxygen, and

(iii) nitrogen oxides mainly resulting from the high temperature values and duration of these high temperatures.

If the richness of the fuel-air mixture is substantially reduced, it is then necessary to increase the rotation speed of the engine to maintain the mass/power ratio of the engine, thereby causing a high increase of mechanical losses and reduction of the working output in a proportion which is generally unacceptable.

To realize an internal combustion engine which is non-polluting and has a high working output, the following conditions should be simultaneously complied with, namely a) reduction of the richness in combustion components of the fuel-air mixture, b) making the ratio "mechanical losses/power" low and independent of the frequency of movement of the pistons, c) lowering of the maximal temperatures and of the time duration of high temperatures.

The present invention provides a free piston internal combustion engine comprising an elongate housing and two like piston units reciprocably movable along a common axis in the housing and defining, with the housing, a combustion chamber between adjacent ends of the piston units, the combustion chamber having intake and exhaust apertures and the piston units being reciprocable under the influence of combustion of a combustible mixture in the combustion chamber and of resilient means provided at the opposite end of each pistons unit, and the piston units having a combined mass within the rangs of 5 grams to 30 grams per cubic centimetre of the maximal volume (as defined) of the chamber, the engine being constructed and arranged to operate, at maximum power, on an intake of a gas-oil mixture, per cycle of movement of the piston units, within the range of 0.01 to 0.02 milligrams per cubic centimetre of said maximal volume or the heat energy equivalent thereof provided by another combustible, and the resilient means being such as to accumulate and return, during each cycle of movement of the piston units, energy in an amount within the range of 0.5 to 2 joules per cubic centimetre of said maximal volume.

The term "maximal volume" means the volume of the combustion chamber immediately after closure of the intake and exhaust apertures.

Preferably a part of each piston unit is made of magnetic material and co-operates with one or more induction coils provided in the housing to produce electric current in the coils when the piston units reciprocate in the operation of the engine.

Preferably each resilient means is provided by an hydraulic load acting on said opposite end of a respective piston unit, the hydraulic load being provided by hydraulic fluid housed within a chamber defined by the housing and said opposite end of the respective piston unit, for compression during each cycle of movement of the respective piston unit. Alternatively, each resilient means is provided by a pneumatic load acting on said opposite end of a respective piston unit, the pneumatic load being provided by gaseous fluid housed within a chamber defined by the housing and said opposite end of the respective piston unit for compression during each cycle of movement of the respective piston unit.

Preferably one or both of the resilient means is arranged to provide an output of energy produced in the operation of the engine,

There now follows a detailed description, which is to be read with reference to the accompanying drawing, of a free-piston internal combustion engine according to the present invention ; it is to be clearly understood that this engine has been selected for description to illustrate the invention by way of example only. The accompanying drawing is a longitudinal sectional view of the engine.

The illustrated free-piston internal combustion engine comprises an elongate housing which is of multi-part construction and comprises a central body indicated by the general reference 1 which defines a cylindrical chamber 8 which intake and exhaust apertures or ports 4, 5 and 6, 7 respectively. Mounted at each axial end of the central body 1 is an induction coil housing 13, 14 which has a through passage coaxial with the cylindrical chamber 8 and three axial recesses for housing induction coils 16, 17 and 18. Mounted on the outer end of each

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induction coil housing 13, 14 is a cylindrical element 19, 20 respectively which is closed at its outer end and defines a cylindrical chamber 21, 22 respectively, the chambers 21, 22 being coaxial with the chamber 8 and of the same internal diameter.

Two piston units 2 and 3 are reciprocably movable within the elongate chamber provided by the chamber 8, the through passages in the induction coil housings and the chambers 21, 22. The piston unit 2 which is reciprocable into the chamber 21 comprises a cylindrical piston head having piston rings which form a fluid tight seal in the chamber 8, a center part of reduced diameter having mounted thereon a plurality of annular discs 11 of a magnetic material and an end part of hollow form which is open to the chamber 21. The piston unit 3 is of similar construction, including a plurality of annular discs 12 of a magnetic material. The two piston units are of the same uniform diameter and are arranged to move simultaneously reciprocably in the operation of the engine between innermost dead center positions in which the end faces of the piston heads are 0.2 cm apart, and outermost dead centre positions.

Each of the chambers 21 and 22 contains hydraulic fluid which provides resilient means of the engine for moving the respective piston unit from its outermost dead center position to its innermost dead center position. The compressibility coefficient of the hydraulic fluid is typically of the order of 50 x 10^{-6} per bar and the pressures exerted on the fluid during operation of the engine are typically in the range of 400 to 1000 bars, so that a substantial compression of the fluid is obtained (as hereinafter described) with a consequent resilience being exerted on the respective piston unit.

The induction coils 16, 17 and 18 and the magnetic cores provided by the annuler discs 11 and 12 have a threefold function. They provide means for starting the engine, means for controlling synchronised reciprocating movement of the piston units during operation of the engine and means for extracting energy, in the form of electric current production, from the engine during its operation. (Other means for extracting energy from the engine can be provided instead of or in addition to the induction coils. For example one or both of the chambers 21 and 22 can be provided each with an inlet and an outlet port so that hydraulic pressures exerted by compression of the fluid in the chambers 21 and 22 can be transmitted to other, hydraulic, systems. Alternatively, the hydraulic fluid can be replaced by a pneumatic fluid and the pressures exerted by compression thereof transmitted to other, pneumatic, systems through the inlet and outlet ports).

During operation of the illustrated engine, fuel is injected into the chamber 8 by a fuel injector 15 and air is drawn in through the intake apertures 4 and 5. Subsequent combustion of the fuel-air mixture when compressed causes movement of separation of the two piston units 2 and 3 to their outermost dead center positions from which they are returned by the resilience of the hydraulic fluid in the chambers 21 and 22 respectively. During the movement of separation, the combusted gases are emitted through the exhaust apertures 6 and 7.

As mentioned above, one of the conditions necessary for obtaining a non-polluting internal combustion engine consists of reducing the richness of the fuel to a value much lower than the one which would require the utilization of large proportion of oxygen. According to the invention, to comply with said condition, the weight of the fuel injected during every cycle of movement of the pistons, under the circumstances a hydrocarbon of the gas-oil type, is limited to a value less than or equal to 1/50 of the weight of the air drawn into and compressed in the chamber 8.

To comply with the above-mentioned second condition, i.e. to reduce the mechanical losses/power ratio and to make this ratio independant of the frequency of movement of the piston units, any positive driving system, as for example connecting-rods, is avoided and the produced power is directly extracted as above described, directly and according to the type of power which is produced.

To comply with the above-mentioned third condition, the quantity of power transmitted to the compressed gas by the piston units as a result of the resilient compression of the hydraulic fluid in the chambers 21 and 22 is limited and the mass of the piston units is minimized. This enables increase of the frequency of movement of the piston units to a value for example higher than 50 cycles per second and consequently reduction of the time duration of high temperatures resulting from combustion in the chamber 8.

The chamber 8 of the illustrated engine according to the invention immediately after closing the apertures 4, 5, 6 and 7 is said to have a volume which is the maximal volume of the chamber and in this case the maximal volume is 200 cubic centimetres. The quantity of fuel introduced by the injector 15 is according to the invention maintained within the range of 0.01 and 0.02 milligram of gas-oil (or the heat energy equivalent of another fuel) per cubic centimetre of the maximal volume of the chamber 8 ; in the present example, the quantity of fuel is 0.015 milligram per cubic centimetre or, in total, 3 milligrams. If it is assumed that the weight of air contained in the chamber is 0.2 gram, the ratio "fuel/air" is of 3/200, which corresponds to a considerable excess of air and to a richness of about 0.22. In such an engine, if the injection of fuel is completed before the piston units reach their innermost dead centre positions and if the atomization of the fuel is adequate, then the combustion will be complete with practically no unburnt products.

Due to the considerable excess of air the formation of carbon monoxide can be almost entirely avoided if the atomization of the fuel in the cylinder, through injection and movements of the gas under high pressure, is satisfactory and produces a homogeneous mixture in the chamber 8.

The resilient means of an engine according to the invention are designed to accumulate and send back a total amount of energy within the range of 0.5 and 2 joules per cubic centimetre of the maximal volume of the chamber 8, and in the example given above where this volume is 200 cubic centimetres, the total amount of energy accumulated and returned is 200 joules. For this purpose, each resilient means contains 200 cubic centimetres of a gas-oil hydraulic fluid compressed upon every cycle of movement of the piston units at a pressure of 426 bars. The compressibility of the gas-oil mixture being 0.000055 per bar, the power accumulated by each resilient means is

$$\frac{0.\ 000\ 055 \times 426^2 \times 200}{20} = 100 \text{ joules}$$

In an engine according to the invention, the piston units have a combined mass within the range of 5 grams to 30 grams per cubic centimeter of the maximal volume of the chamber 8, the mass in the present example being 10 grams per cubic centimeter, or equal to 2 kilograms for both piston units. Each piston unit, having a mass of 1 kilogram, can be returned by the corresponding resilient means at a maximum theoretical speed of $\frac{2 \times 100}{1} = 14.14$ metres per second, which corresponds to an average speed of about 10 metres per second. The operating frequency of the engine is then approximately 100 cycles per second, the duration of every cycle 10 milliseconds and the time duration of the high temperatures, i.e. higher than 1 200°K about 1 millisecond.

The maximum temperature can only result from an overheating of the gas caused partly by the combustion of the fuel injected and partly by about 80% of the mechanical energy returned by the resilient means. If, in the present example, it is assumed that the heating power is 10 calories for 1 milligram of fuel and the average specific heat is 0.25, the overheating of the gas is approximately equal to :

$$\frac{(10 \times 3) + \dfrac{(200 \times 0.8)}{4.18}}{0.2 \times 0.25} = 1\ 360^\circ\mathrm{K}$$

If, upon the closing of the apertures, the gas temperature is 350°K the maximum temperature reached is 1 360 + 350 = 1 710°K.

For such a maximum temperature and a high temperature time duration of 1 millisecond, the quantity of nitrogen oxide produced is extremely small.

The engine, then, does not in practice exhaust poisonous gas and yet the working output of the engine is high partly due to the low heat losses through the walls and due to the low mechanical losses resulting from the absence of any positive drive connections. Besides, the power produced is still high in spite of the low richness of the fuel-air mixture, due to the high frequency of movement of the piston units and working output of the engine.