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Design of marine hydrogen internal combustion engine

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The introduction of new fuel types like hydrogen into the field of maritime transport is considered to be a challenge due to the severe environmental conditions the marine power plant has to work in. Therefore, any attempt to introduce a new technology in this field must be accompanied by sufficient studies and experimental data to provide the engineers and ship operators with enough data about the new fuel type used. This data has to be experimentally approved but in the first and preliminary stages of design of power plants working with new fuels it may not be available or feasible to make large scale experiments, so a computer program is used to give reasonably accurate data about the new design. The demand on energy production will be increased by increasing the population and sea borne trade. The use of other alternatives oil should start to replace diesel oil onboard ships. Hydrogen is considered a good candidate for such replacement. This paper introduces the procedures followed to design a hydrogen internal combustion engine.

تقديم وقودِ جديدِ مثل الهيدروجينِ فى مجال النقلِ البحريِ يعتَبَرُ تحدي بسبب الشروطِ البيئيةِ الحادّةِ التي يجب ان تعمل فيها محطات القوى البحريةِ لذا، أيّ محاولة لتَقديم اى تقنية جديدة فيَ هذا المجال يجب أنْ تُرافقَ بالدِراساتِ الكافيةِ والبياناتِ التجريبيةِ لتَزويد المهندسين والمشغلين بالبياناتِ الكافيةِ حول هذا النوعِ من الوقودِ الجديدِ . هذه البياناتِ يَجِبُ أَنْ تُصدّقَ بشكل تجريبي لكن في المراحلِ الأولى والتمهيديةِ لتصميمِ محطات القوى بالَوقود الجديد وهو قَدْ لا يَكُون متوفرا لاجراء التجاربَ العلمية على نطاق واسعِ. لذا فان برامج الحاسبِ الالَى المستَخدمة لإعْطاء بياناتِ دقيقةِ نسبياً حول التصميمِ الجديدِ قدّ تساعد فى عملية التطوير والتغير. تقدم هذه الورقةِ الخطوات المتبعة لتصميم محرك احتراق هيدروجين داخلى.

Keywords: Engine, Design, Hydrogen, Medium speed

1. Introduction

Internal combustion engine design procedure is an iterative process that requires a large knowledge of different engineering fields, like thermodynamics, machine design, stress analysis, and of course all these fields may not be available to only one engineer with the same level of professionalism, also the time consumed by consecutive iterations to reach logical and feasible solutions cannot be accepted in today's fast changing world. So, the use of a computer program to estimate an initial and preliminary state is a must to decrease both time and cost. In this paper, Engineering Equation Solver EES program is used to solve the problem of engine design and to get a rough estimation of the dimensions of the main components of internal combustion engine running on hydrogen fuel [1].

There is already a substantial production of hydrogen in the world (about 50 million tons annually), for use in fertilizer (ammonia) and methanol manufacture as well as for petroleum refining and South Carolina possesses some of this industrial activity. This production level represents about 1.5 percent of the world's energy consumption, and is growing at 2.1 percent Compound Annual Growth Rate (CAGR). More instructive about the current dynamics in the hydrogen market is the faster growth (5.2 percent CAGR) that is being observed in the segment called the "merchant market" which has experienced sizzling growth as shown n fig. 1 [5].

2. Hydrogen production

Hydrogen is not available as conventional fossil fuels like natural gas, oil and coal so it must be produced either from renewable energy driven electrolysis or from fuel processing of hydrocarbons. Although hydrogen is often touted as a clean energy resource, it is only as clean as the energy feedstock and technologies used to produce it. Currently, the most prevalent and least expensive way to produce hydrogen is to

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derive it from natural gas through a process called "steam reformation." That process, however, generates CO_2 as a by-product. Hydrogen also can be derived from water through electrolysis, but if the electricity is generated from a coal-fired power plant, the "clean" hydrogen also carries with it the upstream emissions associated with coal production, transportation and use. It may be relatively simple to generate hydrogen by electrolysis, i.e. running an electrical current through water; the cost of producing the hydrogen also includes the upstream costs of generating the electricity. If the electricity is generated from renewable energy sources, the cost of hydrogen production includes the costs embodied in renewable power generation.

3. Hydrogen storage

Hydrogen is an extremely difficult gas to store, which will limit its use until convenient and cost effective storage technologies can be developed and commercialised. One gram of hydrogen gas, for instance, occupies about 11 liters of space at atmospheric pressure. So for convenience of use, it must be pressurized to several hundred atmospheres and stored in a pressure vessel. In liquid or compressed form, hydrogen can only be stored under cryogenic temperatures. The following equations represent the change in density (ρ) of hydrogen gas at various temperatures and pressures. These equations are based on the ideal gas law with a compressibility factor (Z) for the hydrogen gas the gas pressure and temperature respectively and R is the gas constant for hydrogen (4157 N m / kg K).

$$\rho = \frac{P}{ZRT} . \qquad (1)$$

$$Z = 0.99704 + 6.4149E\text{-}9\ P. \qquad (2)$$

Where, P (Pa) is the pressure of the gas, V_H (m^3) is the volume and T (K) is its temperature. Using the gas constant given above, eq. (2) can be restated as follows.

$$V_H = Z\,4157.2\ m_H\ T \,/\, P \qquad (3)$$

Where, m_H is the mass of Hydrogen .The tank radius (r) can be calculated from the volume determined in the previous equation. The tank is assumed to be either a sphere or a cylinder with spherical ends. The sphere is actually a special case of the cylinder in which the length (L) is zero. Next equation can be solved for r through an iterative process [10].

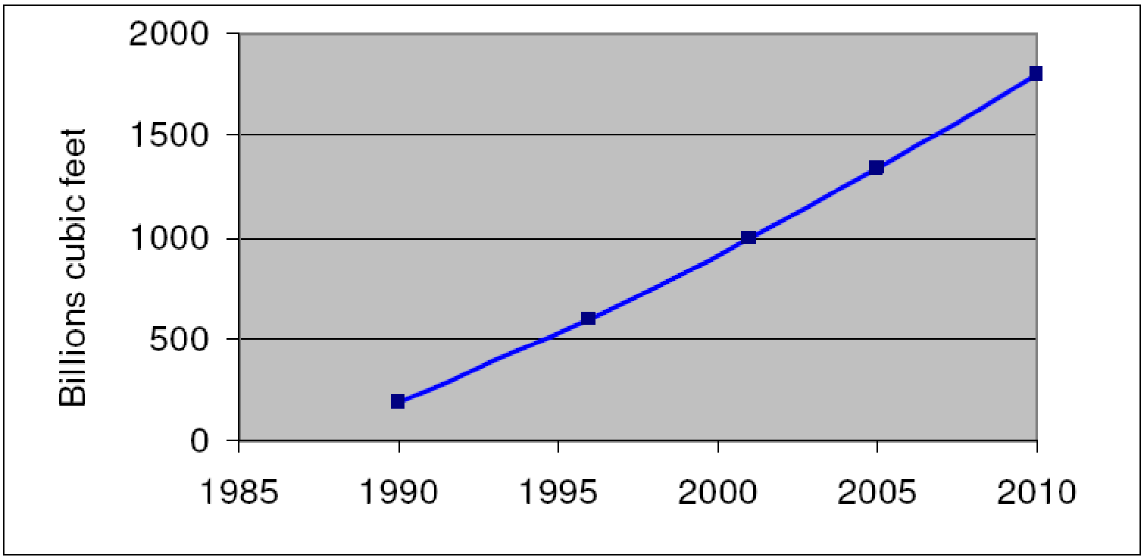

Fig.1. Forecast world wide consumption of merchant hydrogen.

$$V_H = (4\pi r^3 / 3) + (\pi r^2 L). \tag{4}$$

The energy density of gaseous hydrogen can be improved by storing hydrogen at higher pressures. This requires material and design improvements in order to ensure tank integrity. Hydrogen storage depends on the storage pressure and temperature as shown in figs. 2, 3.

4. Thermodynamic design

The first step of engine design is by defining the main requirements needed to be achieved; in this case both power and speed are the main requirements. Power of 3000 kW or 4080 hp and speed of 600 rpm – in the medium speed range – are chosen. These values are determined to make a comparison with the M32C medium speed diesel engine of the well known engine maker MaK, this helps to give good reference values to assess the new design. After determining the main requirements, a standard air cycle must be chosen to approximate the real engine cycle. For hydrogen fueled internal combustion engine, Otto cycle may be reasonably used to simulate the engine cycle due to the high combustion rate of hydrogen which makes the combustion inside the engine cylinders too close to constant volume process [2]. The constant volume Otto air standard cycle is programmed into the EES program using the following four main processes:

Isentropic compression of charge air

- Constant volume heat addition, at fuel injection
- Isentropic expansion (power stroke)
- Constant volume heat rejection

These four processes are detailed next. The previous cycle works between four points, the only known point is point (1), where the air is admitted into the cylinder, the air conditions at this point are known; 100°C temperature and 4 bar pressure, this is the air condition after turbocharging. To determine point (2), the engine compression ratio (*Rp*) must be estimated.

$$Rp = \frac{V1}{V2} . \tag{5}$$

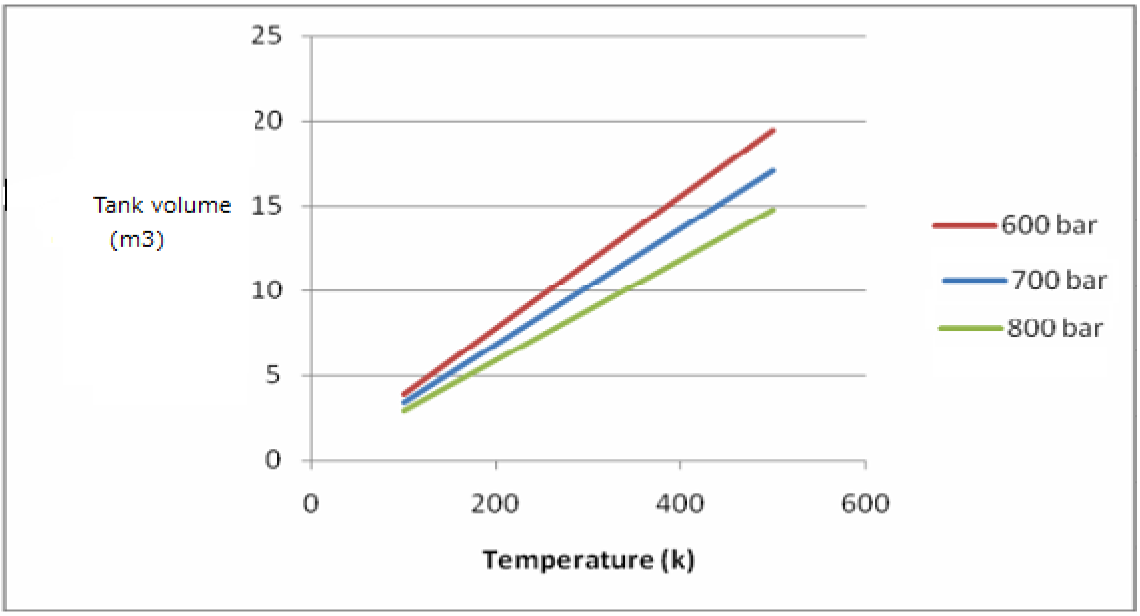

Fig. 2. Relation between tank volume and temperature at different pressures.

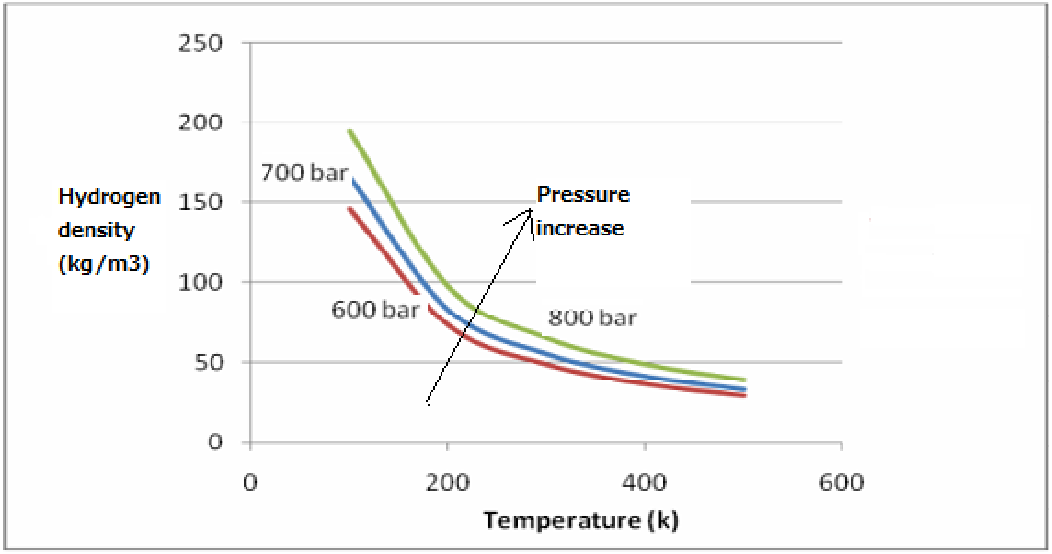

Fig. 3. Relation between hydrogen density and temperature at different pressures.

The EES program can calculate the air specific volume at point (1) without any further programming as all air properties are stored inside. A value of 10 is chosen for (Rp); hence V_2 can be calculated from equation (1). By determining V_2, point (2) is known and any other air property can be calculated. In order to get to point (3), the amount of heat added to the cycle must be first calculated. This heat is the effective heat (Q_{eff}) resulting from the fuel combustion after deducting the amount of heat lost to cooling water. Cooling water losses is guessed to be 30% [2], thus only 70% of chemical energy of fuel will be added to the cycle. Chemical energy of fuel is its calorific value (CV) which is 130,000 kJ/kg for hydrogen [3]. Since the working fluid of the cycle is air and not hydrogen, this calorific value must be corrected to be per kg of air rather than per kg of hydrogen.

$$CV_{air} = \frac{CV}{M_{air}} \quad . \qquad (6)$$

M_{air} is the mass of air entering the engine per kg of fuel and is determined from

$$M_{air} = AF \cdot \lambda. \qquad (7)$$

Where (AF) is the stoichiometric air-fuel ratio and is equal to 34.78 for hydrogen, (λ) is the excess air factor, for this engine it is made constant at 4 to maintain good combustion characteristics.

$$Q_{eff} = 0.7 \cdot CV_{air}. \qquad (8)$$

The internal energy of air at point (3) is that at point (2) plus the amount of effective heat added during process 2-3, therefore, point (3) can be now determined. Process 3-4 is an isentropic expansion process where the air fuel mixture expands to the same volume of point (1), for simplicity, the mixture is assumed to be only air over the entire cycle as shown in figs. 4, 5.

Table 1 resumes all the data of the thermodynamic calculations, assumptions are given first, and then the results of the analysis follow.

After determining the main characteristics of the engine cycle, some processing of the results will lead to determining the main dimensions of the engine. First the number of cylinders is chosen, for good comparison with the ordinary medium speed diesel engine, the same number of cylinders of 6 is chosen. Also, a stroke-bore ratio of 1.5 is taken the same as that of the diesel engine.

$$BHP = \frac{1.02 * P_b * \pi\pi * L D^2 * N * Z}{4*100*60*2*75} \; . \qquad (9)$$

This equation gives the main relation Between Power (*BHP*), engine dimensions (*L,D*), engine speed (*N*), number of cylinders (*Z*) and brake mean effective pressure (P_b). Using this equation, the engine bore and stroke are determined:

Bore = 40.5 cm
Stroke = 60.75 cm

Fig. 6 is generated using the following equation:

$$LCV + \frac{A}{F} C_V T_{air} = \left(\frac{A}{F} + 1\right) CV\, T_{gas} \cdot \tag{10}$$

Where *LCV* is the lower calorific value of fuel, *A* is the amount of air, *F* amount of fuel, *CV* the specific heat of air, T_{air} the air temperature

5. Calculation of dimensions

At engine intake, *CV* the specific heat of exhaust gases and T_{gas} the combustion temperature. [4]

Table 1
Thermodynamic analysis data

Assumptions		
Ambient temperature		27 °C
Ambient pressure		1 bar
Temp. after turbo		100 °C
Pressure water losses		4 bar
Cooling water losses		30 %
Fuel calorific value		130.000 kJ/kg
Excess air factor		4
Compression ratio		10
Results		
Pressure	Point 1	4 bar (assumed)
	Point 2	95 bar
	Point 3	173.8 bar
	Point 4	100
Temperature	Point 1	100 °C (assumed)
	Point 2	613 °C
	Point 3	1348 °C
	Point 4	485.8°C
Engine efficiency		33%
Brake mean eff. pressure		12.76 bar

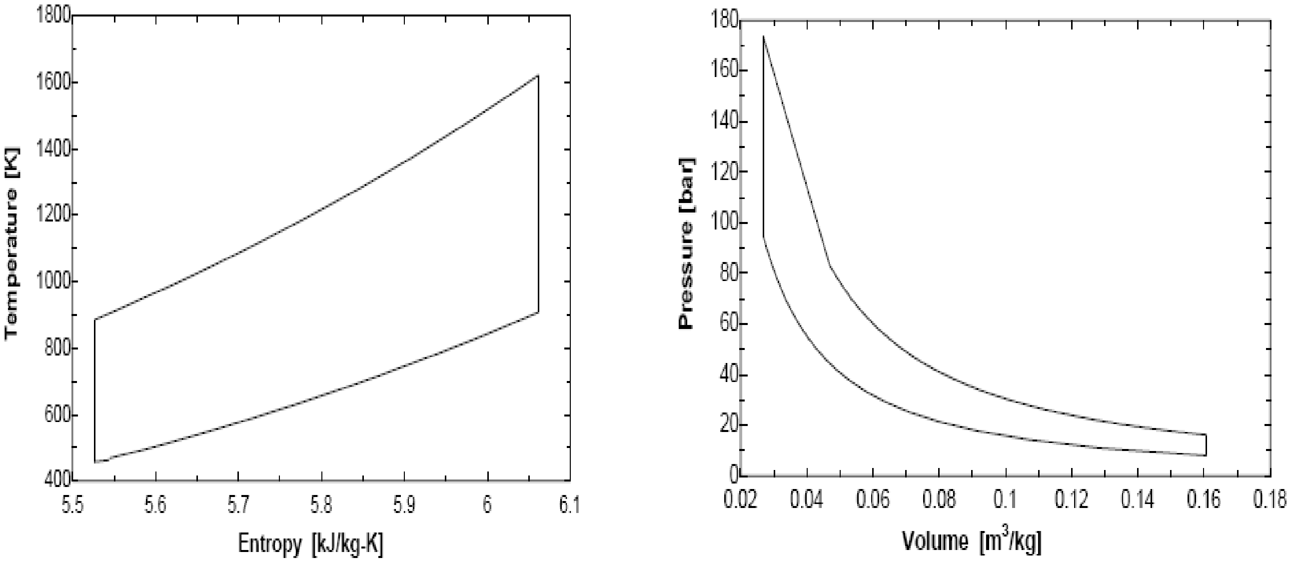

Fig. 4. PV and TS diagrams for the engine cycles.

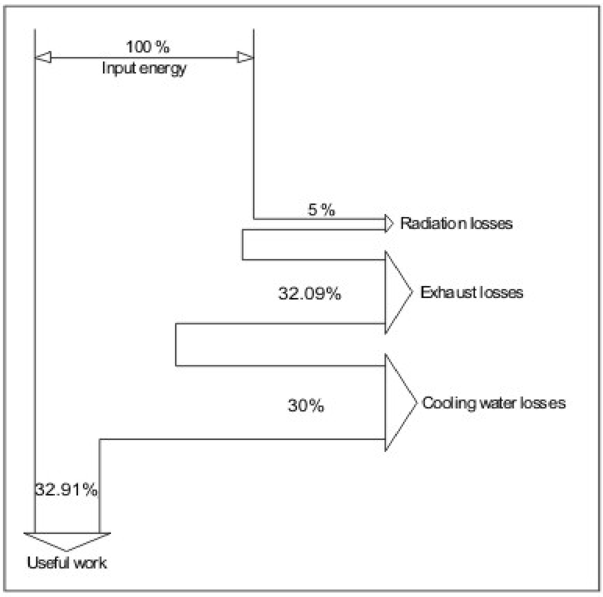

Fig. 5. Engine Sankey diagram.

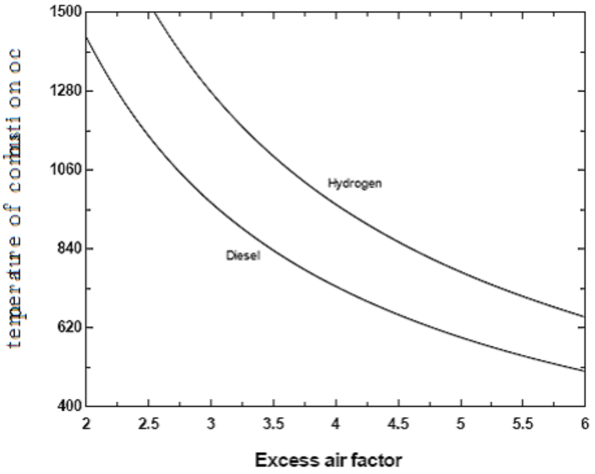

Fig. 6. Comparison of combustion temperature between Diesel and hydrogen [1].

From the above comparison, some points of must be clarified.

- The efficiency of hydrogen engine is less than diesel engine due to higher cooling water losses in the case of hydrogen, without all this losses the temperature of combustion inside the cylinders may reach very high levels that may put the engine in a critical state.
- Due to the higher energy contained in hydrogen, less fuel is used by mass to produce the same power, but the product of fuel consumption and calorific value in both cases will yield a lower value in the case of hydrogen and this is due to lower efficiency.
- Very low brake mean effective pressure is available in case of hydrogen if compared with diesel despite of higher turbocharging pressure in hydrogen engine (in diesel engine only 3.3 bar turbocharging pressure is used), this is due to the different nature of gaseous fuel with very low density (liquid hydrogen density is only 70 kg/m3 [6])
- Due to lower efficiency and lower density fuel, bigger engine dimensions are needed to produce the same power at the same speed of diesel engine.

From the above points it is clear that a lot of work is needed to develop a more feasible hydrogen engine, but it is important to state here that this is only a first solution in a long iterative process to reach optimum design conditions.

6. Main components design

The main components of internal combustion engines are: piston, cylinder liner, connecting rod and crankshaft. Other components like piston pin, piston rings and valves are out of the scope of this paper. The piston is composed of two parts; piston crown and piston skirt, the design of these parts yields the thickness of each. The piston crown is subjected to high thermal and mechanical stresses as this is the part of the engine which is in direct contact with fuel combustion process.

Table 2
Comparison between main engine characteristics of hydrogen engine and M32C engine [5]

	Hydrogen	M32C
Power (hp)	4080	4080
Speed (rpm)	600	600
Cycle	4-stroke	4-stroke
CV of fuel (kJ/kg)	130,000	42,700
Efficiency	33%	47%
No. of cylinders	6	6
Fuel consumption (h/hp.hr)	61.74	131.6
Max. pressure (bar)	173.8	198
Brake mean eff. pressure	12.76	25.9
Stroke/Bore	60/40	48/32

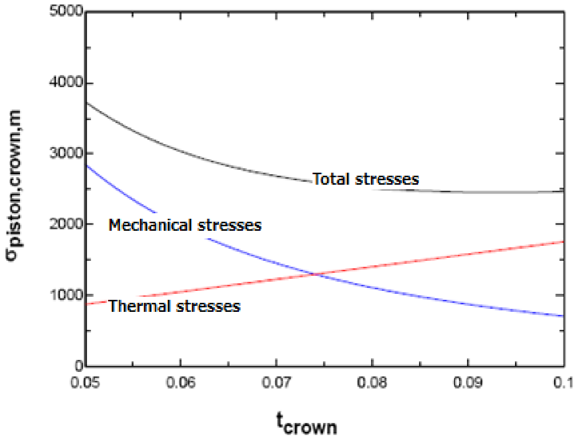

Fig. 7. Mechanical stresses, thermal stresses and total stresses against piston crown thickness.

Fig. 8. 3D model of the piston.

A thickness of 6.5 cm will be a reasonable value to resist both thermal and mechanical stresses.

The piston skirt thickness is taken to be the same as that of the cylinder liner. The cylinder liner is designed also for both thermal and mechanical stresses; the following formula [2] gives the liner thickness.

$$t_{\max.liner} = \left[\frac{D}{2} * \left(\sqrt{\frac{\sigma_{liner.all} + P_{\max}}{\sigma_{liner.all} - P_{\max}}} - 1 \right) + 0.003 \right] * 1.3 \,. \qquad (11)$$

D is the cylinder bore,
P_{max} is the maximum pressure of the cycle, and
$\sigma_{liner,all}$ is the allowable stress for liner material.

The thickness according to this formula is 3.9 cm.

Fig. 9. 3D model of cylinder liner.

Connecting rod design is more complex even if it is not subjected to several thermal stresses as liner or piston. The complexity arises from the fact that the connecting rod is subjected to large dynamic loads due to its trajectory in space. The design is based on tension, compression, bending and buckling criteria. Two main conditions are checked; buckling and combined stresses due to compression and bending as tension forces acting on the rod are not of the same importance as that of compression and bending. First the buckling is checked, according to the design, rod length is 1 m with 14 cm cross section diameter.

$$SL = \pi^2 * E * \frac{I_{rod}}{I_{rod}{}^2} \,. \qquad (12)$$

SL is the safe load to prevent buckling, E is the modulus of elasticity of the material, I_{rod} is the rod section moment of inertia and L_{rod} is the length. According to eq. (12) the safe load is 372.2. bar/m^2 and the maximum force acting in compression calculated from the next formula is 22.39 bar/m^2 which means that the chosen values are not likely to encounter buckling under design conditions.

$$F_{\max} = \frac{\pi}{4} * D^2 * P_{\max} \,. \qquad (13)$$

The force acting on the rod at maximum bending moment position can be calculated from [7]:

$$F_{rod} = \frac{\rho_{steel} * A_{rod} * L_{rod} * \omega^2 * 0.125}{100 * 100} \,. \qquad (14)$$

F_{rod} is the force, *Arod* is the cross section area,
ω is the rotational speed of the engine.

The bending stress (σrod, bend) due to the above force is calculated from:

$$\sigma_{rod,bend} = \frac{2}{3} * F_{rod} * \left(\frac{L_{rod}}{2 * I_{rod}}\right) * d_{rod} . \quad (15)$$

The compression stress ($\sigma_{rod,comp}$) is calculated from:

$$\sigma_{rod,comp} = \frac{F_{\max}}{\frac{\pi}{4} * d_{rod}^{2}} . \quad (16)$$

Equivalent stress for combined compressive and bending effect is the sum of both compressive and bending stresses. This sum must be lower than the value of the allowable stress of the material used.
Allowable stress = 3380 bar
Equivalent stress = 2911 bar (safe)

The design of the crankshaft is of a very high level of importance, it is the most expensive part of the engine and it is subjected to continuous and discrete dynamical loads. The following empirical equation is used to estimate the diameter of the crankshaft.

$$d_{crank} = 1.2 * \left(D^{2} * (0.131 * L + 0.05 * 2 * d_{crank})\right)^{\frac{1}{3}} . \quad (17)$$

The crank diameter from this equation is about 30 cm.

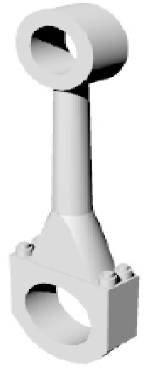

Fig. 10. Designed connecting rod.

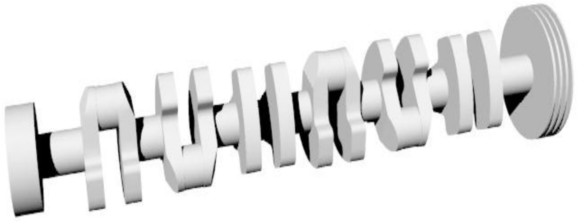

Fig. 11. 3D model of designed crankshaft.

7. Conclusions

The paper presents a brief introduction to how to solve the first step of calculations in the problem of designing an internal combustion engine working with hydrogen. The design results shown in the previous sections may seem strange to the professional reader and yield to heavy, big and expensive engine, but it must not be forgotten that this is a first step, another refinement procedures will follow and also prototype experiments have to be made to assess how far the calculations are from the real world and fine tuning processes will take place after. This procedure can also be applied to different power plants types.Hydrogen gas turbine design can benefit also from the advantages of the computer programs, previous work of the author gives a good idea on how this could be done. [8]

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