THE TEMPERATURE-ENTROPY CHART FOR HYDROGEN ENGINES

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ABSTRACT

The paper deals with the hydrogen engine to be used in motor vehicles. The main dimensions of the engine can be computed from the temperature-entropy T-S chart. The chart is constructed based on MOL combustion gases, when hydrogen burns in air under different values of the excess air factor λ. Then the method of calculation is given.

Keywords: Hydrogen, Temperature, Entropy, Motor-car, Engine

INTRODUCTION

In order to reduce the exhaust gas emissions in motor cars, the combustion efficiency of the benzene fueled engine is improved through the injection of hydrogen in the benzene air mixture entering the engine cylinder.

Furthermore, trials are going on to use pure hydrogen as fuel in the motor car reciprocating engines and Wankel Motor [1-3].

THE COMBUSTION OF HYDROGEN IN AIR

The amount of air necessary for the complete combustion of H_2 can be calculated as follows:

$$2 H_2 + O_2 = 2 H_2O \qquad (1)$$
$$1 + 8 = 9$$

$$\text{Stoichiometric Air} = \frac{8}{0.23} = 35 \text{ kg air/kg } H_2.$$

$$\text{The excess air ration } \lambda = \frac{A}{35 F} \qquad (2)$$

At constant volume, a mixture of H_2 and air, on ignition, gives an end temperature T_g. Thus, with LCV of H_2 =130 MJ/kg.

$$F.\, LCV + A\, C_v\, T_A = (A+F)\, C'_v\, T_g \qquad (3)$$

Dividing by F, then equation (3) reduces to:

$$LCV + \frac{A}{F} C_v T_A = \frac{A+F}{F} C'_v T_g \qquad (4)$$

where, A and F are the air supplied and the fulel supplied, respectively. From Equations 2 and 4

$$130\,000 + 35\,\lambda\, C_v T_A = (35\,\lambda + 1)\ C'_v T_g \quad (5)$$

C_v = 0.84 kJ/kg.K for air C_v = 1 kJ/kg.K for combustion gases, T_A = 400 K

Equation 5 becomes:

$$130\,000 + 35 \times 0.84 \times 400\ \lambda = (35\,\lambda+1) \times 1\ T_g$$
$$130\,000 + 11760\,\lambda = (35\,\lambda+1)\, T_g \qquad (6)$$

The values of T_g for different λ are given in Table 1.

Table 1 Estimation of the end temperature after combustion T_g

λ	A/F	T_g, K	θ_g, °C
1	35	3938	3665
1.5	52.5	2760	2487
2	71	2162	1889
2.5	87.5	1801	1528
4	140	1256	983

THE HYDROGEN RECIPROCATING ENGINE

In order to prevent excessive temperature inside the engine cylinder, it is preferable to limit the value of λ by 2.

Moreover since the combustion of H_2 in air produces water vapor, the lubricating oil must be more water resistant compared to that used in the ordinary engine.

If the lube oil leaks to the combustion space inside the engine cylinder, the following chemical reactions take place:

$$NCO + NO \rightarrow N_2O + CO \quad (7)$$

$$NH + NO \rightarrow N_2O + H \quad (8)$$

$$NO + O_3 \rightarrow NO_2 + O_2 \quad (9)$$

$$NO_2 + O \rightarrow NO + O_2 \quad (10)$$

Hence NO, NO_2 and N_2O will be formed.

NO and NO_2 are toxic, while N_2O contributes in the greenhouse effect or Global Warming Potential.

With λ = 2, the NO_x emissions in the exhaust gases are reduced, but the excess air causes excessive cooling losses, and the brake thermal efficiency of the engine may reach 20%.

The theoretical cycle

The Otto cycle (Constant volume cycle) shown in Figure 1 is applicable here. The highest useful compression ratio (HUCR) of H_2 is 6:1 and the Iso-Octane Number is about 50.

The ratio $k = \dfrac{C_p}{C_v} = 1.4$

Assuming T_1 = 400 K, P_1 = 1 bar, and for different values of λ, the excess air ratio, Table 2 shows the variation in brake mean effective pressure P_b with λ assuming η_m = 85%

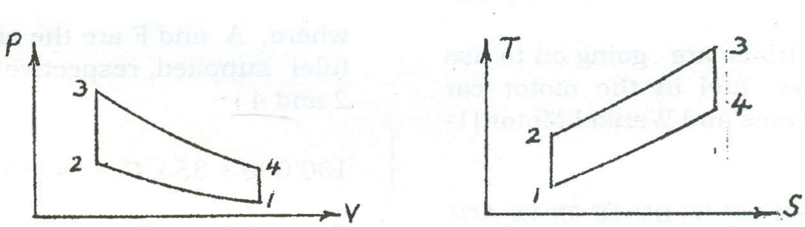

Figure 1 The Otto cycle

Table 2 The theoretical cycle points

λ	P_1	T_1	P_2	T_2	P_3	T_3	T_4	P_4	P_i	P_6
1	1	400	12	800	5.91	3938	1969	4.92	11.78	10
1.5	1	400	12	800	41.4	2760	1380	3.45	7.35	6.25
2	1	400	12	800	32.43	2162	1081	2.7	5.12	4.35
	bar	K	bar	K	bar	K	K	bar	bar	bar

The theoretical indicated thermal efficiency η_{thi}

$$\eta th_i = 1 - \frac{1}{r^{k-1}} = 50\% \quad (11)$$

$$\eta th_b = 0.85 \times 0.5 = 42.5\% \quad (12)$$

These theoretical values will be corrected when the engine cycle is represented on the temperature entropy chart.

The chart will be constructed for, 1 mol combustion gases.

CONSTRUCTION OF THE TEMPERATURE-ENTROPY CHART FOR H_2

The equation for combustion with an excess air factor λ can be written as follows:

$$H_2 + \frac{1}{2} O_2 = H_2O \quad (13)$$

$$H_2 + \frac{1}{2} O_2 \lambda + 3.76 \frac{\lambda}{2} N_2 = H_2O$$

$$+ \frac{1}{2} O_2 (\lambda - 1) + 3.76 \frac{\lambda}{2} N_2 \quad (14)$$

Number of moles before combustion is given by

$$= 1 + \frac{\lambda}{2} + 3.76 \frac{\lambda}{2}$$

$$= 1 + 2.38\lambda$$

$$= 0.5 + 1.19\lambda \text{ per kg Hydrogen} \quad (15)$$

Number of mole after combustion

$$= 1 + \frac{\lambda - 1}{2} + 3.76 \frac{\lambda}{2}$$

$$= 0.5 + 2.38\lambda \quad (16)$$

$$= 0.25 + 1.19\lambda \text{ per kg Hydrogen}$$

LCV = 130 MJ/kg hydrogen

$$= \frac{130}{0.25 + 1.19\lambda} \text{ MJ/mol CG.} \quad (17)$$

Table 3 gives the LCV/MOL CG for different values of λ.

Table 3 The LCV/mol CG.

λ	1	1.5	2	4
LCV MJ/mol CG	90.28	63.9	49.43	25.95

The Universal gas constant R for H_2

$$P = \Upsilon R T$$

$$\Upsilon = 0.089 \text{ at } 1 \text{ bar } \& \ 0°C \quad (18)$$

$$R = \frac{10000}{0.089(273)} = 412 \text{ kg. m/kg.K} \quad (19)$$

and from Equation

$$\frac{mR}{J} = 8.33 \text{kJ / mol.K} = 1.986 \text{ kcal / mol.k}$$

For hydrogen

$$R = \frac{1.986 \times 427}{2} = 424 \text{Kg.m / Kg.K}$$

The products of combustion are shown in Table 4.

Table 4 Products of combustion

	M	Number of moles	R Kg/Kg K	Number of moles λ=1	λ=1.5	λ=2	λ=4
O_2	32	$\frac{\lambda-1}{2}$	26.5	0	0.25	0.5	1.5
N_2	28	$3.76\lambda/2$	30.3	1.88	2.82	3.76	7.52
H_2O	18	1	47.1	1	1	1	1
	Total	Number of moles		2.88	4.07	5.26	10.02

The heat Values

Heat addition at constant volume = U

$dU = MC_v\, dT$ · U at zero K = 0

$$\int_0^T dU = \int_0^T MC_V \, dT \quad \therefore \quad U = \int_0^T MC_V dT \quad (20)$$

Heat addition at constant pressure = H

$$dH = MC_p\, dT$$

$$\int dH = \int MCpdT \quad (21)$$

$$MC_p = MC_v + \frac{MR}{J} = MC_V + 8.33 \quad (22)$$

Example

For λ = 1 O_2 = 0 N_2 = 1.88 mol

and H_2O = 1 mol

at T = 3000 K

from Tables of C_p - T [4]

$M\,C_p\,O_2$ 32 x 1.248 = 39.94

$M\,C_p\,N_2$ 28 x 1.326 = 37.13

$M C_p H_2O \quad 18 \times 3.105 = 55.89$

132.96

$\text{Average } MC_p = \frac{132.96}{2.88} = 46.14 \text{ kJ/mol K}$

$H = MC_p T = 46.14 \times 3000 = 138420$ kJ/mol.

To obtain U, and using Table 4

$MCv\ O_2$	$39.94 - 8.33 = 31.61$
$MCv\ N_2$	$37.13 - 8.33 = 28.80$
$MCv\ H_2o$	$55.89 - 8.33 = 47.56$
	107.97

$$\text{average } MC_v = \frac{107.97}{2.88} = 37.49$$

$U = MC_v T = 37.49 \times 3000$

$= 112470$ kJ/mol

The Entropy

The assumed start point:

$P_o = 1$ bar, T_o 300 K, $v_o = 25.44$ m^3/mol

Entropy at constant pressure

$$S_p = M\overline{C}_p\ \ell n\frac{T_1}{300} - \frac{MR}{J}\ell n\frac{P_1}{P_o}$$

$$= M\overline{C}_p\ \ell n\ \frac{T_1}{300} - 8.33\ \ell n\ P_1 \qquad (23)$$

Entropy at constant volume

$$S_v = M\overline{C}v\ \ln\ \ell n\frac{T_1}{300} + 8.33\ \ell n\frac{V_1}{25.44} \qquad (24)$$

Application of the entropy chart

The Hydrogen engine cycle will be presented on the T-S chart.

For $\lambda = 2$, and using H_2 as the fuel in an engine of the water cooled type then:

$$LCV = 130 \text{ MJ/kg } H_2 = \frac{130}{0.25 + 1.19\lambda} = 49.42$$

MJ/mol C.G.

Assuming 35% cooling water loss, then the effective heat will be 65% x 49.42 = 32.123 MJ/mol C.G.

Air is compressed inside the engine cylinder, then H_2 will be injected.

The mixture of H_2 and air inside the combustion chamber will ignite and the pressure will rise at constant volume.

The cycle is presented in Figure 2.

At point 1: $P_1 = 1$ bar $\quad T_1 = 400$ K

$V_1 = 38$m^3/mol CG.

2: $P_2 = 10$ bar $\quad T_2 = 720$ K

$V_2 = 6.3$m^3/Mol CG.

$U_3 - U_2 = 32.123$ MJ/mol CG.

$U_2 = 17$

$U_3 = 32.123 \quad + 17 \quad = 49.123$

$T_3 = 1620$ K

$T_4 = 1040$ K

$U_1 = 8 \quad U_4 = 30$

$V_1 - V_2 = 31.7$ m^3 /MOL CG.

Heat rejected $= U_4 - U_1 = 30-8 = 22$

Indicated heat $= 32.123 - 22$

$= 10.123$ MJ/mol CG.

$$\overline{P}_i = \frac{IW}{V_1 - V_2}$$

$\overline{P}_i = 3.2$ bar $\quad \eta_{thi} = \frac{10}{49.42} = 20\%$

$\overline{P}_b = 0.85 \times 3.2 = 2.72$ bar $\quad \eta_{thb} = 17.2\%$

For a 4 stroke engine 4 cylinders 50 BHP at 4000 RPM and with D = L

$$BHP = \frac{\overline{P}_b \cdot V_s \cdot N}{900}$$

V_s = stroke volume = 4.41 liters

$4\ \frac{\pi}{4} D^3 = 4.41 \quad D - L \cong 11$ cm

and BHP / liter = 12

(For comparison in modern benzene engines BHP/liter = 50).

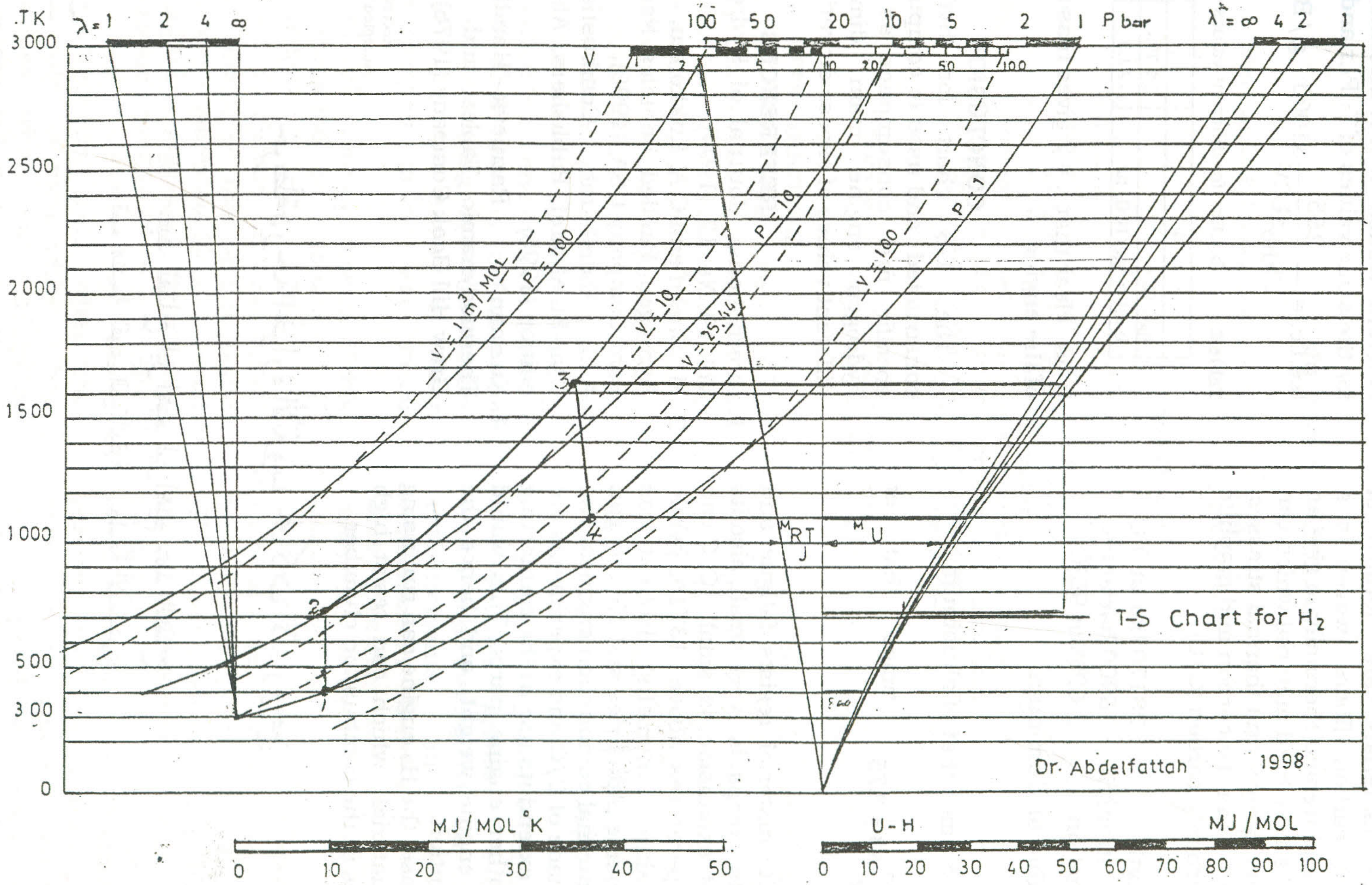

Figure 2 The cycle on the T-S chart

THE ROLE OF COMPOSITE MATERIALS IN IC ENGINES

Composite materials are formed of thousands of carbon fibers woven in a special way and treated thermally to give an end product: a very hard material which can resist high mechanical and thermal stresses.

The fibers can be carbon and graphite (Kevlar) or carbon / carbon (C/C)

Tensile strength	28170 bar at 0°C
Compression strength	16900 bar at 0°C
Tensile elongation	1.62% at 90°C

Density = $\frac{2}{3}$ that of aluminum

Stiffness = 2.5 times that of aluminum

$\frac{\text{Stiffness}}{\text{weight}} = \frac{2.5}{2} x3 = 3.75$ times that of aluminum.

This C/C material resists fatigue and corrosion. Its creeps is very small, also its coefficient of expansion is small. C/C can sustain temperatures above 1371°C (while at 600 °C aluminum melts). 1970 it was used in airplane industries and 1990 began its use in internal combustion engines. The piston is made of C/C and experiments are going on to extend its use in the connecting rod, and other engine parts. This would reduce the engine weight, and hence the fuel consumption.

In this case, the H_2 engine can run using the new material which can resist high temperatures in the combustion chamber.

The specific H_2 consumption

The specific fuel consumption for different values of λ is indicated in Table 5, for the same values of T_1,P_1,r and CWL%.

$$b.s.f.c. = \frac{2.65}{\eta_{thb} x LCV} x1000 \quad g / BHPhr.$$

Table 5 b.s.f.c. for different values of λ

λ	1	2
η_{phb} % =	16.7%	17.2
b.s.f.c.=gr/BHP hr	122.3	118.5

It is clear that λ = 2 gives reasonable b.s.f.c of the engine.

CONCLUSION

The T-S chart for hydrogen was constructed and used to compute the brake specific fuel consumption as well as the hydrogen engine main dimensions for different values of excess air ratio λ.

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ملخص البحث

لتصميم محركات الاحتراق التى تستخدم الايدروجين، يستحب تمثيل الدورة الحرارية على خريطة درجة الحرارة - الانتروبيا. تم استنباط الخريطة وأعطى مثال لاستخدامها فى تصميم المحرك.