Hydrogen wet combustion And “Water Vapor Pump-cycle”

Combustion humide de l’hydrogène Et cycle de la « Pompe A Vapeur d’Eau »

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ABSTRACT. The so-called “water vapor pump” cycle is defined by the selective recycling of the water vapor carried by the combustion products at the outlet of the thermal machine by exchange of mass and heat between the exiting combustion products and the incoming atmospheric air. With hydrogen fuel, this form of wet combustion is capable of very high energy and ecological performance.

In this context, we present here the Combustion Hydrometric Combustion Diagram (CHD) of hydrogen and apply this tool to anticipate the energy performance of this new fuel whose gcv exceeds its ncv by 18%. These expectations also concern the case of gas turbines in the case of wet combustion which, moreover, are, a priori, highly consuming additional water. The formation of atmospheric water plumes, the "cost" of its elimination, the possible residual pollution due to NOx are also presented, this concerning the use of hydrogen fuel in all thermal combustion machines, including in fuel cells.

All applications combined and in a cogeneration context, wet combustion, of which the so-called “water vapor pump” cycle is part, increases the dew point temperature of the combustion products by approximately 10°C and promotes useful energy recovery. approaching 100% of the gross calorific value of the fuel (100% of the gcv). What is to be emphasized with hydrogen fuel.

RÉSUMÉ. Le cycle dit “ Pompe à vapeur d’eau“ se définit par le recyclage sélectif de la vapeur d’eau véhiculée par les produits de combustion en sortie de machine thermique par échange de masse et de chaleur entre les produits de combustion sortant et l’air atmosphérique entrant. Avec le combustible hydrogène, cette forme de combustion humide, est susceptible de très fortes performances énergétiques et écologiques.

Dans ce contexte, nous présentons ici le Diagramme Hygrométrique de Combustion (DHC) de l’hydrogène et appliquons cet outil pour anticiper les performances énergétiques de ce nouveau combustible dont le PCS dépasse de 18% son PCI. Ces anticipations concernent aussi le cas des turbines à gaz en cas de combustion humide qui, par ailleurs sont, a priori, fortement consommatrice d’eau additionnelle. La formation de panache d’eau atmosphérique, le « coût » de son élimination, la possible pollution résiduelle due aux NOx sont également présentés, cela concernant l’utilisation du combustible hydrogène dans toutes les machines thermiques à combustion, y compris dans les piles à combustibles.

Toutes applications confondues et dans un contexte de cogénération, la combustion humide dont le cycle dit « pompe à vapeur d’eau » fait partie, augmente la température de rosée des produits de combustion d’environ 10°C et favorise une récupération exploitable d’énergie approchant 100% du pouvoir calorifique supérieur du combustible (100% du PCS). Ce qui est important à souligner avec le combustible hydrogène.

KEYWORDS. Hydrogen, Combustion, wet, Recycling, Steam, Water, Performance, Energy, Environment, Diagram, Hygrometric, gcv.

MOTS-CLÉS. Hydrogène, Combustion, humide, Recyclage, Vapeur, Eau, Performance, Energie, Environnement, Diagramme, Hygrométrique, PCS.

1. Introduction

We know the environmental qualities of hydrogen and the current enthusiasm for its application in internal or external combustion engines or fuel cells.

It is less well known that its qualities as a fuel in gas turbines and internal combustion engines are at least as great when wet combustion is projected. A combustion which, in principle, cools the adiabatic combustion temperature and reduces the formation of nitrogen oxides, also ensuring, and if necessary, better completion of combustion for certain fuels.

From the outset we also emphasize that the higher calorific value of hydrogen (gcv) exceeds its lower calorific value (ncv) by 18%. Which also means the interest in considering mass exchanges aimed at the condensation of water vapor resulting from combustion for maximum recovery of useful energy in thermal processes using this supposedly carbon-free fuel.

In these cases of so-called wet combustion where additional water is introduced into the combustion chamber, we also know that the recycling of condensates resulting from the process can avoid external water consumption which is costly to produce and store. Thus hydrogen, the combustion of which produces a lot of water vapor, is a fuel that is becoming relevant.

This relevance can nevertheless lead to reacting to avoid plumes of water coming out of chimneys and other exhaust pipes...

For all this, a diagram called combustion hydrometric diagram (CHD) was developed to anticipate specific performances and provisions from the 1980s for the case of methane and its fumes deemed a little too “condensing” for certain architects of the 1960s.

In this article we present the hydrogen CHD and will apply it to anticipate the behavior of mobile or fixed installations using this fuel - including in the case of fuel cells - and practicing a form of wet combustion (water injected directly or introduced with the oxidant or even the fuel). [GUI 11,79,04,19][KUC 96].

2. The CHD presentation

2.1. *General case [EST 95][HEB 98][GUI 98,00,02]*

Initially intended for work concerning the energy applications of combustion, this diagram firstly offers easy access to the enthalpy of the combustion products leaving a thermal process with combustion.

It assumes complete combustion of the fuel and offers a graph established for standard atmospheric conditions (the software allows one-off applications and plots when there is a significant deviation from these standard conditions: air at 21% O2 at 15° C, pressure 1013 hPa, humidity 8 hPa.

The 3 main axes of the CHD (fig.1)

-X axis: Enthalpy of combustion gases Hpc: related to the gcv: Hpc expresses the energy efficiency or yield; the choice of gcv reflects the prospect of recovering the latent energy of the water vapor produced by combustion)

-Y axis: Wet temperature of combustion products TH; In the case where mass exchanges are probable, we know the relevance of the wet temperature

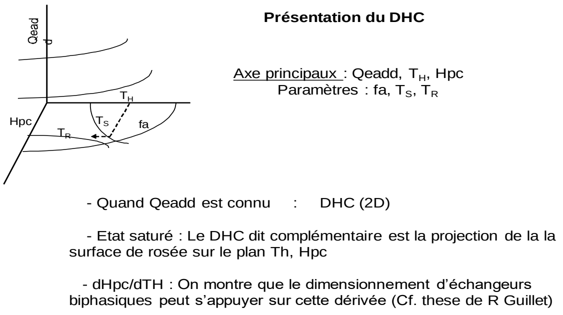
About TH spotting:

Immersing the wet bulb in a flow of hot gases, TH is identified by the temperature level recorded before the probe, which has become dry, leaves again towards a new level which is the dry temperature of the gases (TS). The hotter the gases are and above their dew point temperature (TR), the shorter the plateau, becoming only an inflection point that is increasingly difficult to spot.

-Z axis: Quantity of additional water per mole of Qeadd fuel. If this quantity is negative then water is evacuated in liquid form. There has been condensation in the process (“condensing process”).

When Qeadd is known, the CHD is reduced to a plane where the air iso-factor fa (=excess air+1), the dry isotherms, appear as long as TS is greater than the dew temperature TR. the TR curve which follows the evolution of TR with fa is drawn. The TR values being read by projection on the TH axis (Y axis).

Thus is presented in Figure 3 the plot of the CHD of the hydrogen fuel when Qeadd =0 (neither addition nor condensation of water in the process).



Présentation du DHC

Axe principaux : Qeadd, T_H, Hpc
Paramètres : fa, T_S, T_R

- Quand Qeadd est connu : DHC (2D)

- Etat saturé : Le DHC dit complémentaire est la projection de la la surface de rosée sur le plan Th, Hpc

- dHpc/dTH : On montre que le dimensionnement d'échangeurs biphasiques peut s'appuyer sur cette dérivée (Cf. these de R Guillet)

Figure 1. *The 3 main axis of the CHD : Qeadd, TH, Hpc*

2.2. *The complementary diagram*

In the context where mass exchanges are possible, let us repeat that the dry temperature is no longer very relevant [GUI 98]. Also to access the Hpc values, a so-called CHD-complementary diagram is established (effectively forgetting the TS isotherm plots), projecting onto a single plane (X,Y) curves corresponding to discrete values of air factor fa and the TR dew curves associated with discrete values of Qeadd, the TR values always being read on the TH (Y) axis.

2.3. *CHD and the thermodynamic first law*

CHD allows a relevant application of the first law of thermodynamics in a context of mass and thermal exchanges. And more precisely when there is combustion.

Considering a process or system with combustion, this law teaches us that having chosen the references (temperature and hygrometry) the difference between the incoming and outgoing enthalpy flows corresponds to the sum of the work W and the heat Q supplied by the system, as defined, to what is external to it. Since the enthalpies are related to the gcv of the unit of quantity of fuel entering (here the mole) The potential enthalpy due to combustion has the value "1". Thus, comes the diagram in Figure 2 where, in relation to the reference conditions Hpc is the enthalpy of a mole of fuel (generally zero if the conditions of introduction are those of the references held for it). The same goes for Ha which concerns the incoming air. Likewise for He which concerns water, capable of mass exchange and must be, according to the reference which concerns it, considered in the liquid or vapor phase. The software established for the CHD program allows the calculation of all these incoming enthalpy flows.

As for the outgoing enthalpy, it is carried by the combustion products, called Hpc (which is the basis of the establishment of the CHD graphs (3D, 2D and complementary versions).

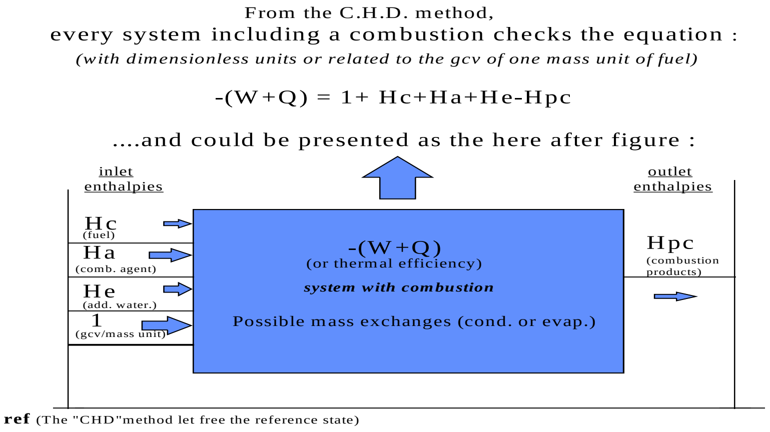


Figure 2. *The first thermodynamic law*

3. Hydrogen CHD or the Hpc value

As indicated above, Figure 3 represents CHD-2D of hydrogen when there is no additional water, It is said CHD/Qeadd=0.

Figure 4 ignores the dry temperature values of the combustion products. It represents the CHD-complementary to hydrogen.

The main axes (reminder)

Vertical axis: enthalpies of combustion products (Hpc % gcv)

Horizontal axis: saturating temperature (humid or dew TH or TR in °C)

The 3rd axis Qeadd can be visualized as orthogonal to the two previous axes, the value of Qeadd expressed in mole of water per mole of fuel becoming negative when the point representative of the state "E" corresponds to supersaturated combustion products (presence of condensates).

Secondary routes (reminder)

Air iso-factors fa

TS dry isotherms

The dew curve functions from fa where the trace of the TS isotherms ends.

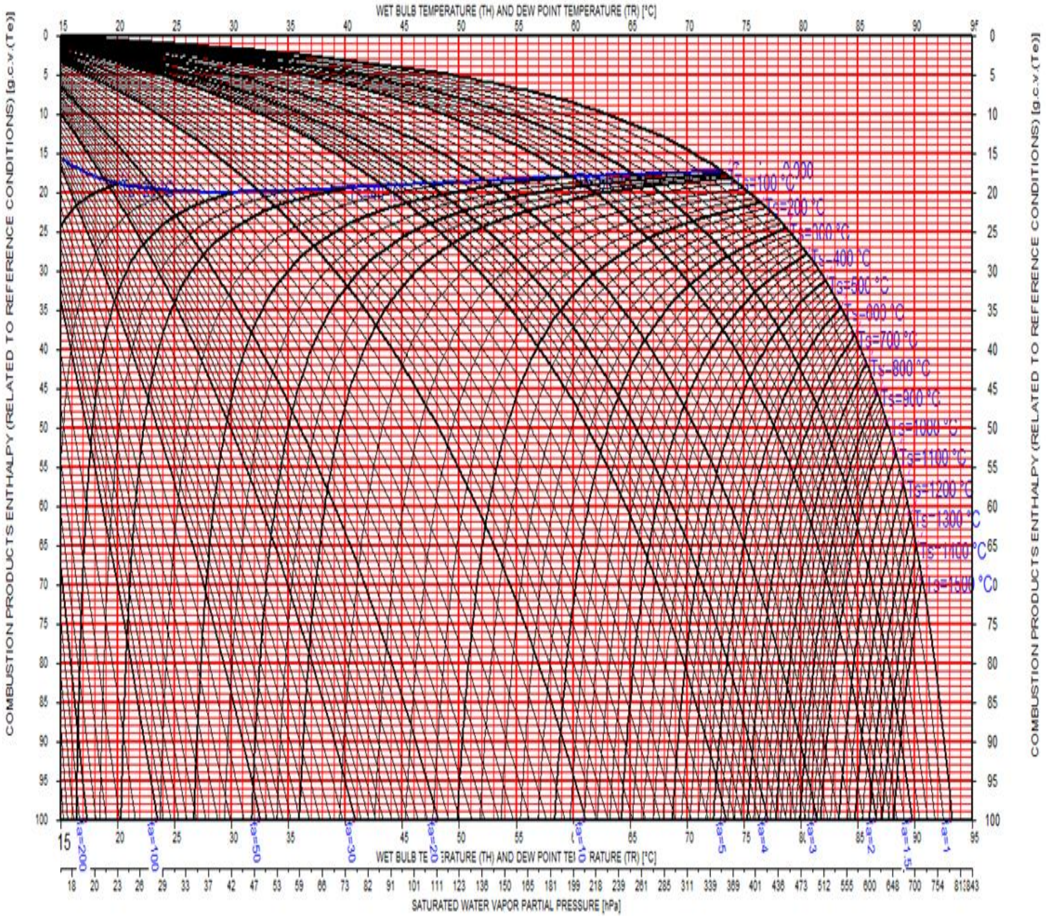


Figure 3. *Hydrogen CHD/Qeadd=0*

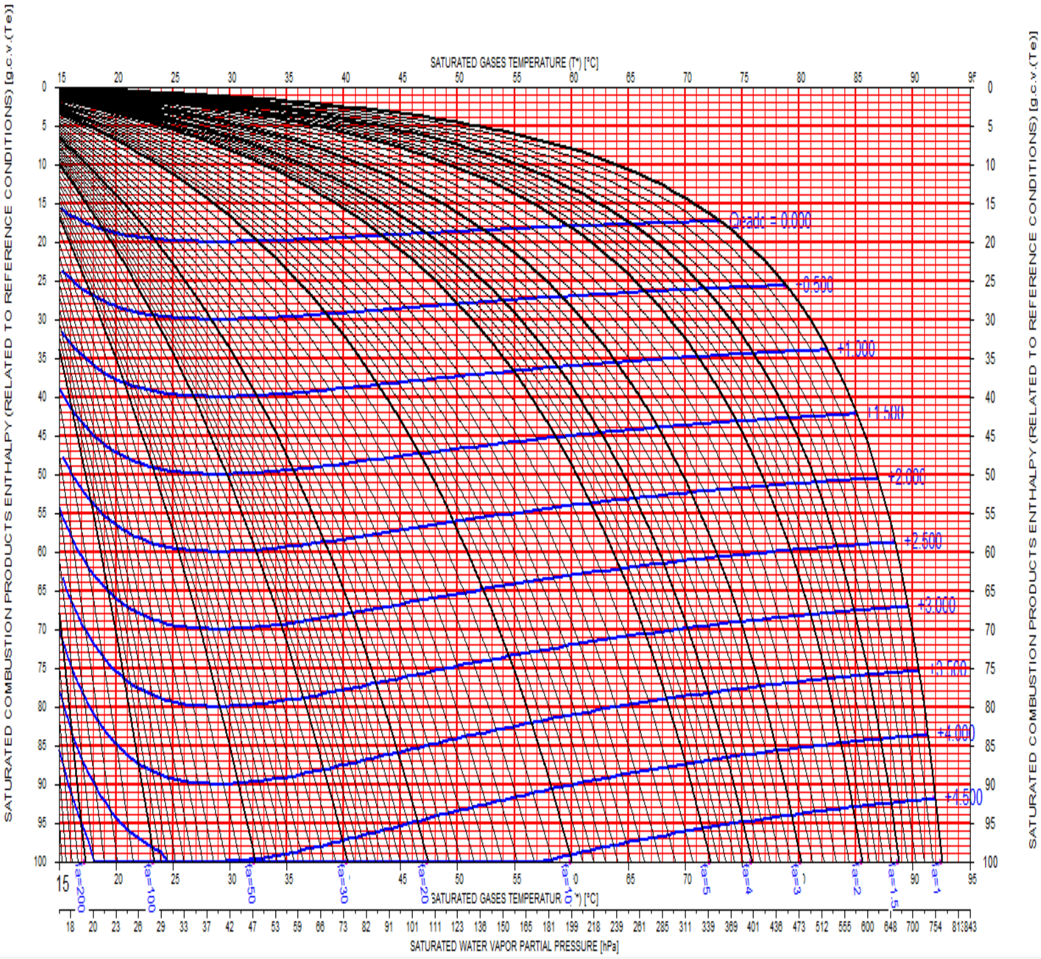
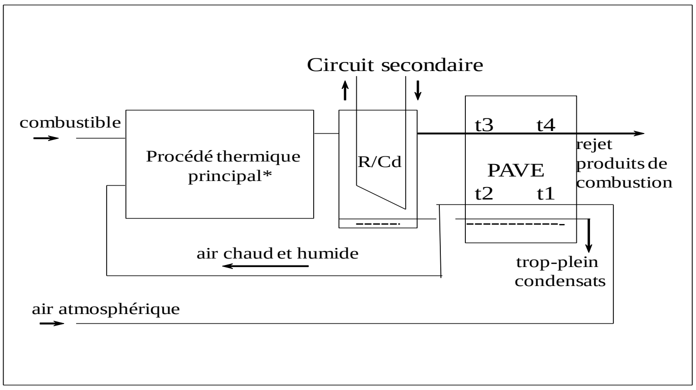


Figure 4. *Hydrogen complementary CHD*

3.1. *CHD using for Hydrogen fuel combustion efficiency anticipation in process running the WVP-Cycle (fig.5)*



R/Cd Condensing-Recuperator
WVP or PAVE (mass and heat exchanger for water recycling called “water vapour pump”)
t1, t2, t3, t4 are wet bulb temperatures
*Main process or procédé th. principal : cogénération, internal combustion engine, gas turbine, boiler, direct dryer, fuel cell etc.

Figure 5. *The WVP-cycle*

The ultimate exchanger called the water vapor pump (WVP) selectively recycles and after condensation the combustion water necessarily generates a form of wet combustion with its energy and ecological advantages (reduction or even elimination of NOx, particularly welcome when the fuel is immediately decarbonized and it is the last pollutant [GUI 02].

For the cycle to be effective in terms of thermal recovery, the WVP exchanger is preceded by a recuperator-condenser which supplies the utilities with thermal energy, essentially latent (see fig. 5).

In the case of cogeneration, the effective heat recovery Q of this R/Cd exchanger will depend on the temperature requirements coming from the “utilities” (heat networks for example).

In other cases, it will be the power demand W which will be optimized by priority by the operator.

3.2. *WVP-Cycle energetic efficiency anticipation thanks to the CHD*

Observing Figure 6 where point “A” represents the state of the combustion products leaving the thermal process and entering the enthalpy recycler called WVP the maximum possible exchange with the incoming atmospheric air (recycling efficiency 100%) would cause the combustion products to be released with zero enthalpy if its value is related to atmospheric conditions. Since the gases are evacuated supersaturated with water, and unless special provisions are made, the temperature cannot be lower than the humid temperature of the ambient air.

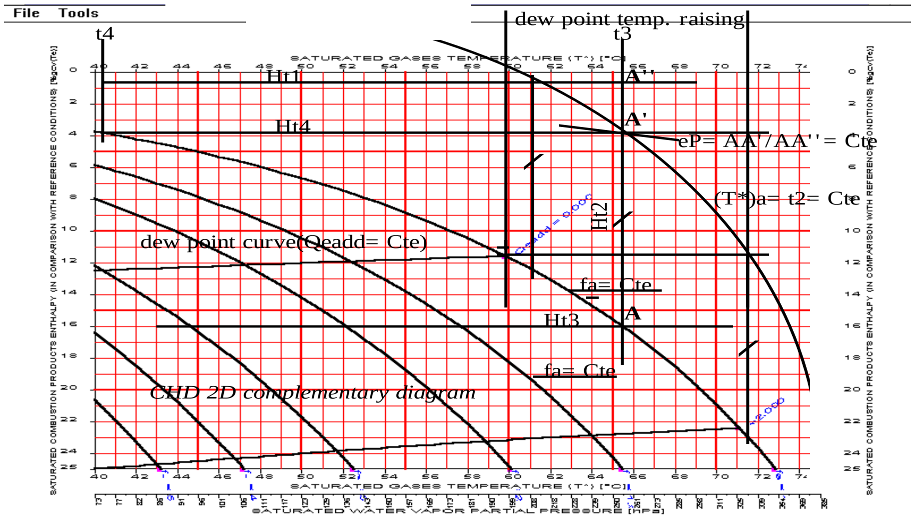
If the efficiency of the WVP exchanger increases their temperature from t3 to t4 the efficiency “eP” of the PAVE is defined by the ratio of enthalpies (ht3-ht4) / (ht3-ht1) = AA'/AA' '
An iso-efficiency curve can be drawn by moving point A according to the iso air factor fa = Cte and respecting constant the value of the ratio AA'/AA" (translation according to the vector AA').

The wet temperature of the air leaving the WVP exchanger is very close to the wet temperature indicated by the intersection of the isenthalp passing through A" with the curve (T*)a =t2= Cte which is obtained by translation of the curve fa = Cte which passes through the point A, following the vector AA'; the higher the value of fa, the more these two values can be confused).

By humidifying the combustion air, WVP-Cycle induces an increase in the dew point temperature of the combustion gases compared to combustion with atmospheric air. This elevation corresponds, for the same air factor fa, to the temperature difference between the dew point temperature associated with the same value of the air factor fa due to combustion with ambient atmospheric air and the corresponding point with the intersection of the same isenthalpic line with the isotherm t2. In figure 6, the increase in dew point temperature ΔTR due to the recycling carried out in the PAVE is ΔTR=11.5°C, TR increasing from 60 to 71.5°C.

WVP-cycle efficiency anticipation: dew point temperature raising

The water vapor pump thermal efficiency anticipation



The values that we can read here come from the combustion of methane and are significantly more favorable in the case hydrogen combustion for which the gcv / ncv gap is double that of methane; the increase in the dew point temperature mentioned ΔTR= dew point raising = 11.5°C), is due to the recycling of water carried out by the mass and heat exchanger that is the WVP exchanger

Figure 6. *Graphic anticipation of a WVP exchanger efficiency with the CHD complementary diagram*

OBSERVATIONS

Since the water vapor pump does not exchange with the outside (except for wall losses), the value of the exchanges with the outside W+Q does not change, the analysis concerns the thermal system which includes the water vapor pump exchanger or the same thermal system which excludes it (see figures 2 and 5).

As explained in reference [GUI98], chapter 2, the value of the wet temperature TH of the combustion products is a relevant indicator of the enthalpy of the combustion products in a context of mass exchanges concerning water. Its knowledge, or even its measurement, is therefore to be favored, especially when the quantity of additional water Qeadd is unknown. Likewise, the use of complementary CHD could then be favored.

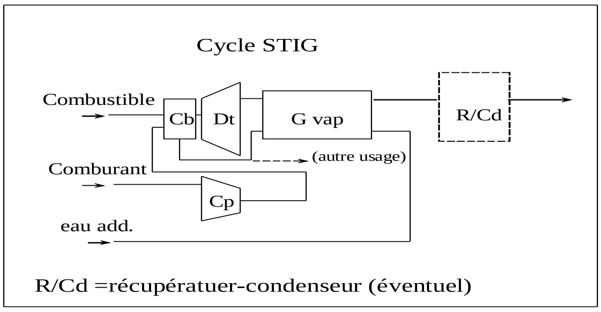
The water vapor pump is, a priori, an exchanger connected in a sealed manner to the recuperator-condenser which precedes it, sealed from the air inlets; the flow of gas passing through it corresponds to a constant factor identified on the CHD.

The implementation of the WVP-cycle promotes high performance for heat generators or cogenerators thanks to an increase in the water dew point temperature reaching 12°C (compared to a configuration without additional water), i.e. 72°C when the fuel is methane and 85°C if it is hydrogen (increase remaining a function of the efficiency of the WVP exchanger and which may be limited by the rate of oxygenation of the concomitant oxidizer which must not put into effect the combustion quality.

3.3. *CHD application to anticipate efficiency of a gas turbine running a wet combustion: the STIG – Cycle example* ***[GUI 92]***

The CHD calculation software also helps to anticipate the performance of traditional gas turbines or those using wet combustion, including in cases where the consumption of new water is avoided. The WVP-Cycle thus offers the prospect of more “complete” cogeneration efficiency, with maximum environmental efficiency, i.e. maximum condensation of gases before discharges. And we recall here that compared to traditional fuels, the combustion of hydrogen produces a lot of water.

The STIG (Steam in Gas or Cheng) cycle described in Figure 7 is a wet cycle in competition with the HAT (Humidified Air Turbine) cycle or even with the Maisotsenko cycle (the latter being characterized by cooling of the air coming from the compressor which goes below its wet temperature to reach its water dew temperature). If this cycle is not the most efficient regarding its mechanical efficiency (mechanical power W produced), according to a global approach, costs in particular which lead to taking into account the size of the machines, their weight, this cycle allows more options technological for the introduction of additional water. It is therefore chosen here for the following comparison.



Cp: air compressor; Cb: combustion chamber; Dt: expansion turbine;
G vap: steam generator and its overheating); R/Cd: recuperator-condenser
Figure 7. The Steam In Gas Turbine cycle (also known as Cheng)

Figure 7. *The STIG -Cycle*

Concerning the comparison between the fuels, methane and hydrogen, from the point of view of the maximum mechanical efficiency Wmax for cycles of Joule, STIG, WVP, all ideals defined by the same compression ratios (=10) and same temperature of entry into the expansion turbine (=1000°C), the values of fa, Qeadd which maximize W are then determined and retained the value of the wet, dry, dew temperatures at the outlet of the expansion turbine.

For the WVP-Cycle, the efficiency retained for the mass and heat exchanger allows the cycle to avoid any consumption of new water.

Previously, with the associated software we establish the values fa and Qeadd then the enthalpy of compression of the air, that linked to the expansion of the combustion gases up to the expansion temperature Tdt which correspond to the compression ratios (=10) and temperature (=1000°C). Generally, by priority of thermodynamic efficiency, the combination (fa, Qeadd) which maximizes the value W will be sought.

The operating parameters fa and Qeadd having been determined, we proceed according to the indications presented in chapter 3. The point “A” which combines fa and Tdt can then be plotted on the CHD diagram relating to the value of Qeadd. Then we operate according to the indications in paragraph 3.2 to achieve the heat recovery objectives that we have set (the eP efficiency of the mass and heat exchanger will then be specified). If measuring TH is possible at the expansion turbine outlet, we can choose to use the complementary CHD to define an “A premium” point and access the Hpc value at this level, i.e. Hpcdt. In both cases, the value of W = Wexpansion/gas – Wcompression/air, is equal to 1- Hpcdt. Crossing the R/Cd recuperator following (most often) the air iso-factor fa =Cte will lead to point “A” in correspondence with entry conditions into the PAVE exchanger (in accordance with the presentation of the figure 6).

According to the STIG-cycle, the use of additional water injected into the combustion chamber (in large quantities, several molecules per fuel molecule) is the characteristic of this cycle which aims to approach the performance of the Joule + Rankine cycle. It is then relevant to consider recycling the water carried by the combustion products leaving the engine and the proper operation of the recuperator-condenser (R/Cd) up to avoid new water consumption (and a water storage tank when on-board engine !), can become an important objective. In the case of power production with (useful) heat recovery, the implementation of the WVP-Cycle allows the system to aim for an optimized overall performance close to energy recovery equal to 100% of the fuel gcv.

Results of comparative anticipation for three cycles and two fuels (CH4 and H2)

	fa	Qeadd (molH2O/ mol.of fuel	TR °C	W % PCS
CH4 Joule	3,59	0	46,3	25,5
CH4 STIG	2,78	8,51	69,1	38.7
CH4 STIG+PAVE	2,50	9,30	70,3	38,2
H2 Joule	*4,23*	*0*	*37,5*	*25,9*
H2 STIG	*2,00*	*3,60*	*81,1*	*38,9*
H2 STIG+PAVE	*1,95*	*3,70*	*82,7*	*37, 8*

Anticipations show that the mechanical performances obtained with hydrogen fuel are very close to those obtained with methane. As for the "WVP" effect, although it has little effect on power production, it improves the temperature level of latent condensation heat recovery in the R/Cd heat recuperator, the quantity of which is particularly important in the event of combustion of 'hydrogen. It is anticipated that, when switching from methane to hydrogen, on average, the dew point temperature of the combustion products increases by more than 10°C.

For the size of the turbochargers (compressor and expansion turbine), the “size” ratio can be based on the compared values of fa for the air compressor and fa and Qeadd for the expansion turbine. Without forgetting, to refine this comparison between the two fuels, that the ratio (theoretical air x fa)/gcv will also have to be taken into account [GUI02].

Finally, it must be emphasized that these are “idealized” expectations and that experimental results are very desirable.

Furthermore, in light of what has just been observed for gas turbines, we can see the validity of the enthusiasm of certain car engine manufacturers and other light vehicles for the combustion of hydrogen in internal combustion engines, going so far as to explore the path of wet combustion in order to avoid “lining” and any external cooling water circuit for the cylinders.

4. Graphic study of water plume formation and its elimination “energetic cost”

We know that smog can be a combination of fog and NOx. And this combination can produce ozone at low altitude: a gas which is also dangerous for our health and more generally for living species and in particular trees near highways, airports, etc. In other cases, the plume can induce other risks, for example in cold countries the risk of icy formation near chimneys, or another visual nuisance (or even making it too easy for planes to locate in the sky!).

It then becomes important to anticipate the formation of water plumes at the smoke outlet and the DHC is a relevant tool.

Using the atmospheric conditions at the chimney outlet as a reference state to establish the DHC, the atmospheric diffusion of combustion products at the chimney outlet appears as an isenthalpic phenomenon (horizontal line of the CHD).

4.1. *General case (non-saturated fumes exhausted)*

Point C in Figure 8 represents the state of the combustion products at the exhaust or at the outlet of the chimney.

Atmospheric dilution can be considered to be isenthalpic. The tangent at the lowest point of the curve defined by the dew temperatures as a function of the air factor fa is plotted.

If point C is above this tangent, a plume is formed and will be eliminated if we accept an enthalpy cost Δh (= 1.20% gcv, in the example given in figure 8), to be brought to the flow of gas before discharge (for example via a draft cutoff at the bottom of the chimney passing from C to C').

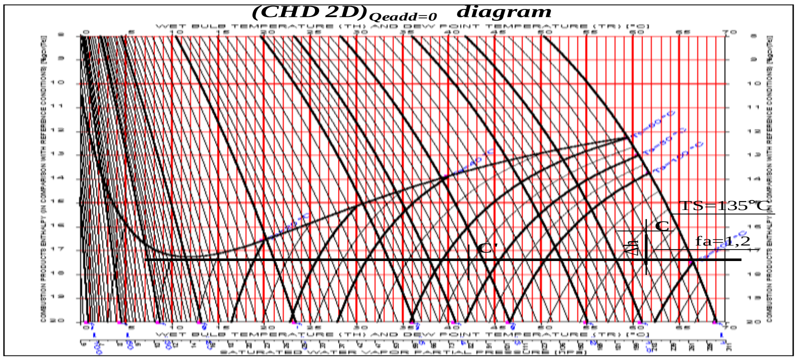


Figure 8. *Plume anticipation: CH4 fumes example*

4.2. *When exhausted gaz are saturated (coming from a condensing process or a WVP exchanger)*

This is a WVP-Cycle which retains 1.42 moles of water per mole of fuel in the form of condensates.

The CHD-2D corresponding to Qeadd = -1.42 is established and we observe that it is sufficient to provide the fumes with Δh = 0.85% gcv, to eliminate the risk of a plume of water vapor at the chimney outlet (see figure 9).

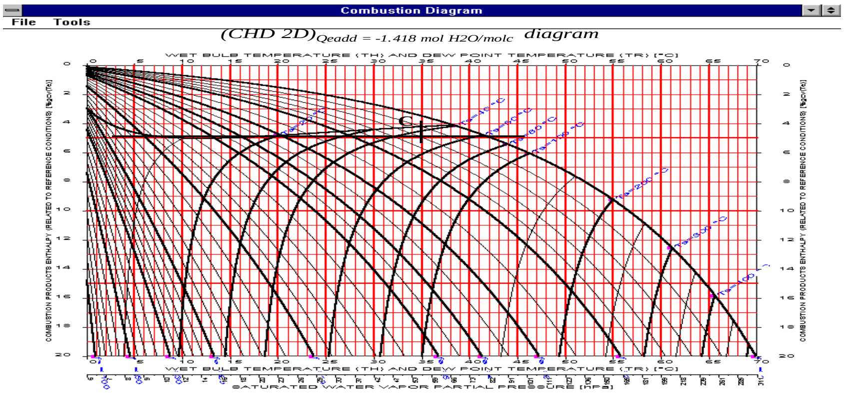


Figure 9. *Plume anticipation in case of oversatured CH4 fumes example*

It should be noted from these two cases (figures 8 and 9) that, if the outgoing gases are saturated (or even supersaturated), the "enthalpic cost" of eliminating the plume risk can be reduced compared to a configuration where high energy performance is sought. With condensation before rejection, therefore corresponding to a Qeadd value <0, the dew curve becomes “flatter” with atmospheric dilution, that is to say when *fa* increases!).

5. Humid combustion and NOx

With or without WVP-Cycle, the introduction of additional water during combustion reduces the combustion temperature, therefore acts to reduce the formation of NOx [CAI 99] and, as we recall, on the proper completion of combustion, particularly in the case of fuels deemed difficult. We remember “orimulsions”, “aquazoles” and even the measurements observed on condensing boilers burning methane and using the WVP-Cycle.

As with all fuels, when it comes to hydrogen, the combustion temperature (oxidation-reduction) affects the formation of nitrogen oxides, the ultimate pollutant but still very formidable on the ground, particularly to be feared in an urban environment in the event of smog, the combination of the two favors the appearance of ozone. Thus, as with any thermal combustion engine, and taking into account the comparatively very high water content of the combustion products of hydrogen, the addition of water reducing its combustion temperature (exceeding 2200°C with traditional air) will reduce the formation of NOx while controlling water plumes will go in the same direction of reducing health risks.

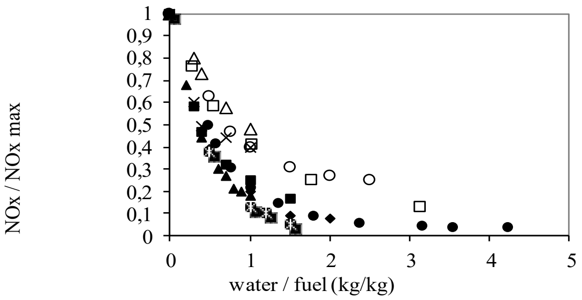


Figure 10. *Compilation from many authors studies [11, 12, 13, 14, 15, 16] the results retained from a compilation, the NOx/NOx max ratio referring to the case of the same combustion configuration with atmospheric air (therefore observed on various burners with various fuels.*

6. Conclusions

After its ability to increase the power and efficiency of certain thermal combustion machines, the use of water opens the door to energy saving and simultaneously to the reduction of the environmental impact of the oxidation-reduction of a “primary” energy.

With hydrogen and its potential ecological advantages, combustion produces an unusual quantity of water and the control of its condensation, its selective recycling, offers new perspectives for its use for all thermal machines where oxidation-reduction takes place.

In this context, the cycle of the water vapor pump which recycles practically all the combustion water in the combustion chamber, can also avoid the consumption of new water, the need for a water storage tank on-board, also broadening the possibilities of optimization and valorization of the recovery of sensible and latent heat in an R/Cd condensing-recuperator, to finally approach energy performances close to 100% PCS and remarkable ecological, the WVP exchanger being also to be considered as a tool for optimizing the distribution between demand and supply of power W and heat Q.

However, experimental work remains necessary, particularly with the new fuel of hydrogen, in order to confirm what is expected.

Thus, we believe that this article will contribute to providing strong motivation to future experimenters, inevitably numerous, when we know the craze for the new fuel and particularly when it is of natural origine!

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