

The Combustion Hygrometric Diagram (CHD) software (*for Windows XP*)

- Guidebook ⁽¹⁾ -

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(1) Explanation and examples of use can also be found in “Wet Way Combustion” book (by Rémi Guillet / Elsevier ed. 2000 or in “Du diagramme hygrométrique de combustion aux pompes à vapeur d’eau” (by Rémi Guillet / Elsevier ed. 1998) or by consulting the Rémi Guillet thesis “La combustion par voie humide et ses performances” at:

[www.scd.uhp-nancy.fr/docnum/SCD T 2002 0149 GUILLET.pdf](http://www.scd.uhp-nancy.fr/docnum/SCD_T_2002_0149_GUILLET.pdf)

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(3) Rémi Guillet* has developed the CHD during his activities as R and D engineer more than forty years ago and has launched the first CHD software for PC in cooperation with the INSA Rouen early in the nineties.

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Abstract

The CHD software is a useful tool for analysing, improving, optimizing the efficiency of any processes including a combustion and particularly relevant for condensing processes as condensing boilers or processes using additional water to increase their heat and power efficiency and, as a more and more appreciated consequence, a more “ecological” combustion in the last case we have called “humid combustion processes”.

This numeric tool can be also the base of a new metrology using the wet bulb temperature as a main data... And is also relevant to size any kind of bi-phases exchanger, as the “water vapour pump”, to detect any inside or outside water condensation...

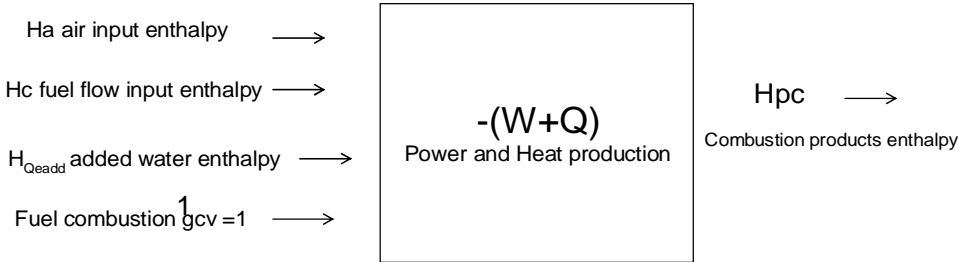
<p>This new version of the CHD software is fitted to work on Microsoft Windows XP (or Microsoft Windows 7) and can be obtained by touching CERTI SPEA at hebert@insa-rouen.fr</p>

The CHD calculation assumes a complete fuel combustion and is a strict application of the first thermodynamic law

Using the 1st thermodynamic law and the property of the enthalpy extensivity (additivity) we can write

$$W+Q = 1+H_a +H_c + H_{Q_{eadd}} - H_{pc} \quad (1)$$

where referring to the chosen references conditions, H_a H_c $H_{Q_{eadd}}$ H_{pc} $W+Q$ values are expressed related to the fuel gcv (and $W+Q$ is the Heat and Power efficiency related to the fuel gcv)



After introduction by the user of the physical data, of the fuel, of the combustion agent, of additional water (if there is!) and these of the exhaust combustion products, the CHD software calculates the H_a , H_c , $H_{Q_{eadd}}$, H_{pc} enthalpies and “ $W+Q$ ” values (All these enthalpies being expressed relating to the fuel calorific value). Because of the context of water phase change, the considered above calorific value is the gross calorific value (gcv).

Always because of this context (of phases change), the reference conditions to express all the enthalpies must be detailed. After the reference temperature T_e , the moisture reference retained for the combustion agent, for the fuel moisture must be indicated... while the reference phase for the additional water (Q_{eadd}) is always the liquid phase at T_e .

Then, the real conditions of the inlet fuel humidity, combustion agent humidity must be detailed while the added water must be detailed by the vapour quantity and temperature inlet (Q_{eaddv} and T_{eadd}) and by the liquid quantity and temperature inlet (Q_{eaddl} and T_{eaddl}).

If we choose the real ambient air (combustion agent) conditions as reference conditions to express the enthalpies value, then the combustion agent enthalpy is null, the fuel flow inlet enthalpy is generally negligible... and if there is no additional water, then we can write:

$$W+Q = 1-H_{pc}$$

Assuming that all gases considered have the property of semi-perfect gases, the calorific capacities (at constant pressure) C_p are not dependant of the pressure (if T is the temperature then $dH=C_p.dT$). Nevertheless, the pressure value has to be considered because of the context of water phase change!

The CHD software is an outstanding tool to study combustion processes particularly when a water phase change in the combustion products is provoked or possible.

Generally speaking it's also a tool offering new and unusual measurements to easily obtain the $W+Q$ efficiency value of any systems with combustion...

To separate W and Q needs the second law application. Here, we suppose that the user is skilled enough in cycle knowledge to know when there is only Q production (as in boiler, oven, kiln...), or a quasi-only W (as in gas turbine...). If not, we point that the efficiency known thanks to the CHD software will be the co-generation efficiency (the $W+Q$ "total").

The CHD images

Because of the relationship “ $W+Q = 1+H_a+H_c+H_{qeadd} - H_{pc}$ ” we can present the CHD picture in a 3-D dimension space.

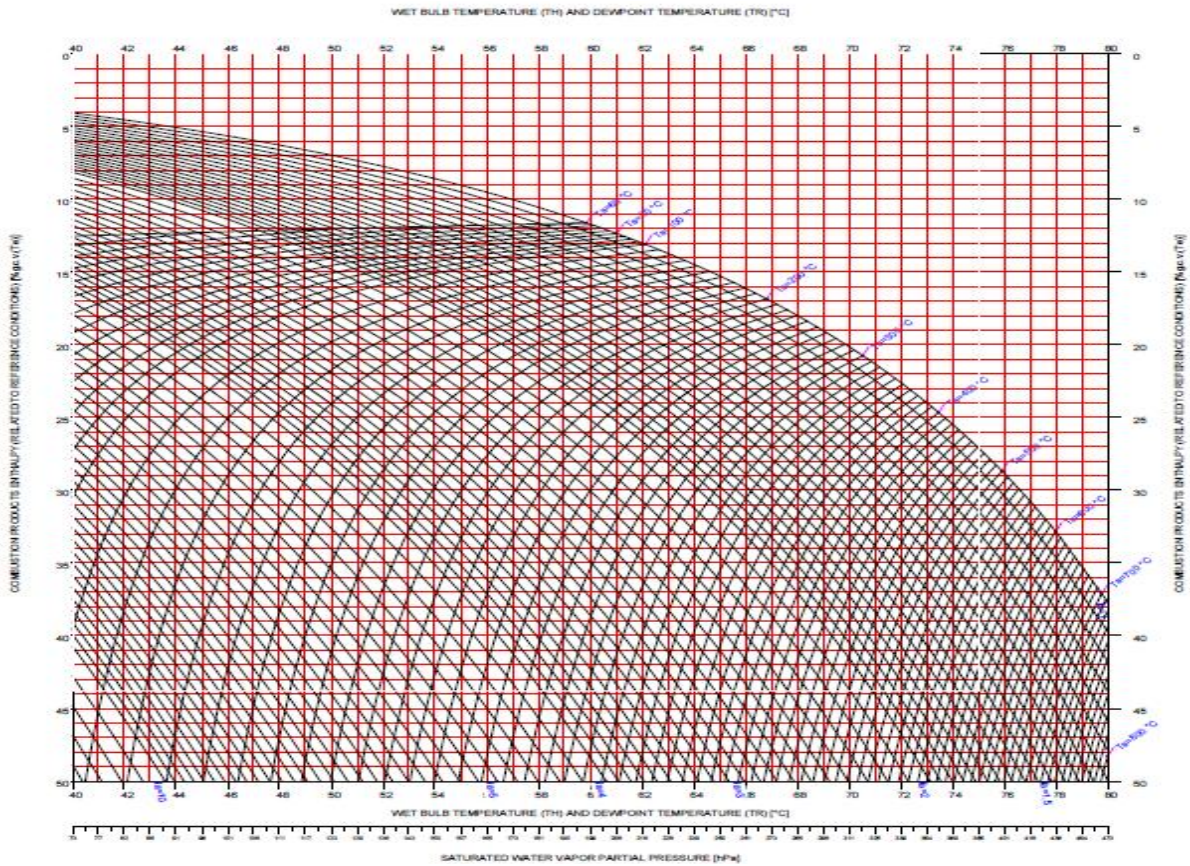
But, when the “ Q_{eadd} ” value is known and constant, a CHD 2-D diagram can be drawn. Then we have chosen the wet bulb temperature of the combustion products “ T_h ” and their enthalpy “ H_{pc} ” as main axes for this 2-D diagram.

For each 2-D diagram (for which Q_{eadd} value is constant) a bundle of curves appears when we consider different configurations of iso-air factor (f_a value)...

An other bundle appears by considering different iso-dry temperature of the combustion products (“ T_s ” value). This last bundle being boarded by the iso-air factor curve “ $f_a=1$ ” and a saturated curve called the dew point curve (curve obtained by junction of all the dew point temperature “ T_r ” associated to each iso-air factor curve ($f_a = \text{constant}$). (The dew point temperatures value being always read by projection of the considered dew point T_r on the T_h axe).

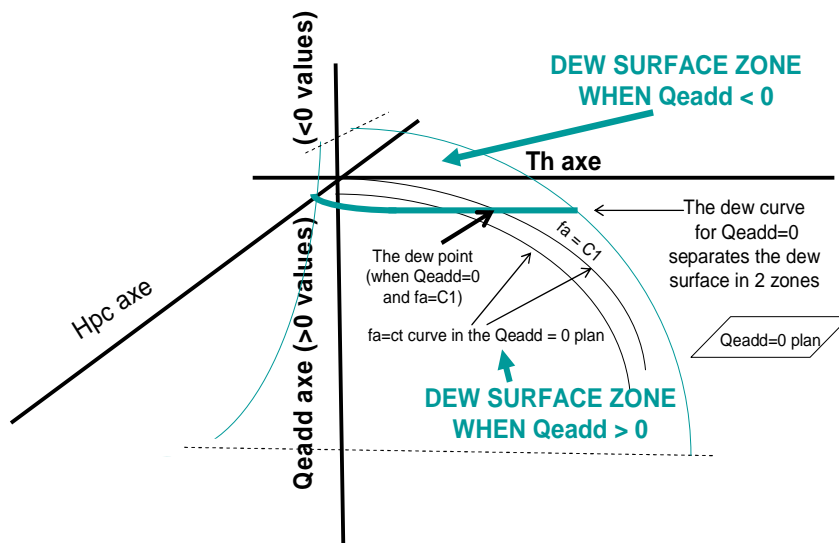
By the fact, on one side of the dew point curve, the combustion products are “oversaturated” and on the other side they are “dry”.

A 2-D diagram shape



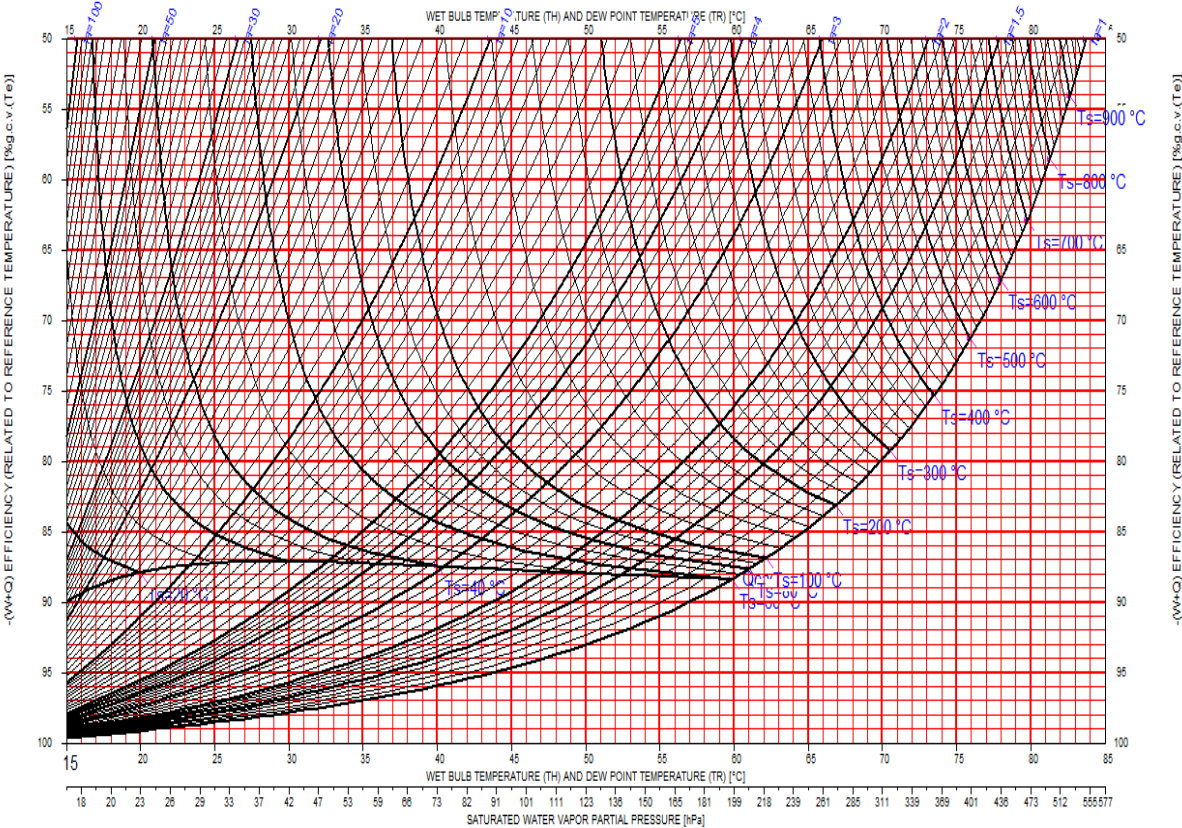
Now, changing the additional water value “Q_{add}”, (which constitutes the third main axe in a 3-D space) a “dew surface” appears in this space...

The 3D diagram and dew surface shape



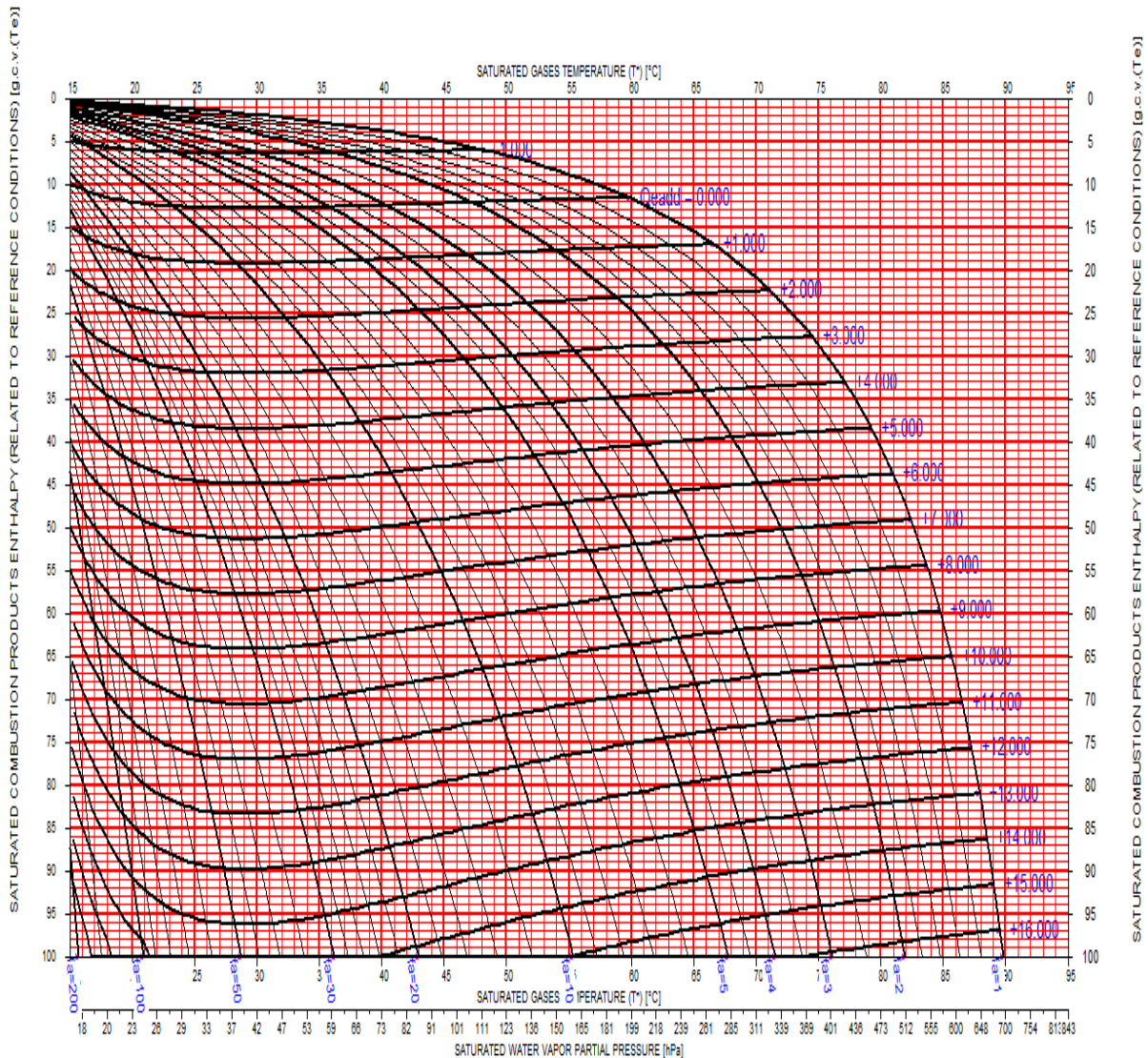
But, because of the relationship (1) we can also choose $W+Q$ as chief axe (taking the place of H_{pc})...

An other 2-D diagram shape ($W+Q$ is a major axe)



The complementary CHD graph

We obtain the complementary CHD graph when the called “dew surface” is projected on the Th / Hpc plan, by following the Qeadd axe. And a graph as here after appears...



But the CHD software results are also displayed in numerical data screens...

THE CHD SCREENS

Screen *Units and reference conditions*

Combustion Hygrometric Diagram

File Help

Units and reference conditions | Fuel characteristics | Combustion agent characteristics

Reference conditions

Temperature (Te) : 15.00 °C

Combustion agent total pressure (Ptae) : 1013.250 hPa

Combustion agent hygrometry (Pteae) : 8.000 hPa

Fuel total pressure (Ptce) : 1013.250 hPa

Fuel hygrometry (Ptece) : 0.000 hPa

Units

Temperature : Celsius [°C]

Pressure : hectoPascal [hPa]

Energy : kiloJoule [kJ]

Comment for user

THE IMPERATIVE DATA TO ENTER

T_e (reference temperature for enthalpy value calculation):

In case of gaseous fuel:

P_{tae} (reference total pressure of the combustion agent)

P_{PH_2Oae} (reference water vapour -absolute-pressure in the combustion agent)

In case of liquid or solid fuel

If the fuel is a liquid (fuel oil) or a solid fuel (wood, coal...) then the reference state will be the same fuel without any water inside.

Screen *Fuel characteristics*

Example of screen *Fuel characteristics*

Combustion Hygrometric Diagram

File Help

Units and reference conditions | **Fuel characteristics** | Combustion agent characteristics | 2D point | 3D point | Comple

Méthane

Fuel type

Liquid or solid fuel : % mass Gaseous types

(%mass H, C, S, N, O) relating to 1 kg of fuel (/ kgc)

% mass. (H) : *****

% mass. (C) : *****

% mass. (N) : *****

% mass. (O) : *****

% mass. (S) : *****

Total : *****

g.c.v. (Te) : ***** kJ/kgc

Average Cp = ***** kJ/(kgc.°C)

Fuel composition

% mol. % vol.

Name	% dry gas
Methane(CH4)	100.0000
Ethane(C2H6)	0.0000
Propane(C3H8)	0.0000
n-Butane(C4H10)	0.0000
2-Methylpropane(C4H10)	0.0000
n-Pentane(C5H12)	0.0000
Isopentane(C5H12)	0.0000
Neopentane(C5H12)	0.0000
Total :	100.0000

Water partial pressure in fuel (PpH₂O,c) : 0.0000 hPa

Fuel total pressure (Ptc) : 1013.2500 hPa

Fuel temperature (Tc) : 15.00 °C

Open

Save

Comment for user

In case of gaseous fuel the gcv value is calculated automatically by the CHD software and displayed when the user clicks on “save”.

THE IMPERATIVE DATA TO ENTER

T_c (real temperature of the input fuel) : °C

If it's a gaseous fuel...

The composition of the final equivalent dry mol of fuel called “molc” is usually expressed in % of each initial component and the CHD software calculates automatically the gcv value of one unit of quantity of dry fuel.

To take account of the real gas moisture we must indicate,

P_{tc} (real total pressure of the input fuel)

$P_{PH_2O_c}$ (real water vapour -absolute- pressure in the input fuel)

If it's a liquid (or solid) fuel...

Then the unit of mass is usually the kg of dry fuel and the fuel composition is expressed by % of C, % of H... in the "dry" fuel.

In this case the gcv (of a dry fuel unit) must be introduced by the software user.

As already said, in this case, the associated humidity is considered as additional water (Q_{eadd}) and the water quantity is expressed by each kilogramme of "dry" fuel (Q_{eadd}/kgc).

(The real input temperature of this water associated to the liquid or solid fuel will be indicated).

By clicking on the fuel can be load from a previous saved composition by the software.

By clicking on the last data are recorded for a next use.

Screen Combustion agent characteristics:

The CHD software provides a psychrometric module able to find the combustion agent data (referring to the chosen reference conditions).

THE IMPERATIVE DATA TO ENTER

The combustion agent composition: % of O_2 , N_2 , CO_2 and others components in the dry combustion agent...

The real combustion agent moisture:

P_{tc} real total pressure of the input combustion agent

T_a real inlet temperature of the combustion agent

And a third data chosen among the 5 under:

$T_{h,a}$ wet bulb temperature of the inlet combustion agent °C

$h_{r,a}$ relative hygrometry of the inlet combustion agent %

$P_{PH_2O_c}$ real water vapour-absolute-pressure in the input combustion agent
 hPa

h_a (absolute value of the water contained in the dry combustion agent
dry agent) kg/kg

$T_{r,a}$ (dew point temperature of the combustion agent) °C

Then h_a/m (enthalpy per kg of dry combustion agent will appear in the screen displaying the results, expressed as a result (and expressed in kJ/kg of dry combustion agent).

NB: After introduction of 2 parameters, the maximum value of the third parameter is displayed to avoid a stupid error ...

If the real f_a value is indicated, then $H_{a,Th,a}$ (air inlet enthalpy associated to the combustion of one unit of fuel, $N_{H_2O\ sat, Th,a}$ (quantity of water contained in the saturated combustion products at T_{ha}) will appear.

This screen also displays other data coming from some $H_{a,Th,a}$, $N_{H_2O\ sat, Th,a}$ derivatives expressions / T_{ha} (as “coda”, “codPhia”, “Cpa, T_{ha} ” ... All data which are useful for exchanger sizing (the method of sizing anticipation is announced at the end of this guidebook and more completely explained in the appendix associated to the guidebook provided with the software tool delivery).

Example of screen Combustion agent characteristics

Composition in combustion agent		Cp,a,Ta	
<input checked="" type="radio"/> % mol. <input type="radio"/> % vol.		0.323	kJ/(mol.°C)
		If fa=1 then Ha (gcv(Te))	0.218 % if not Ha(fa) = Ha(fa=1) × fa
Oxygen :	20.946 % of dry	The parameters below for the saturated state at Th,a g.c.v. (Te).Coda(Tha) 0.707 kJ/(mol.°C) g.c.v. (Te).CodPhia(Tha) 0.384 kJ/(mol.°C) Cp,a,Tha 0.323 kJ/(mol.°C) Ne,sat(Tha) 0.131 mol/molc	
Nitrogen :	78.102 % of dry		
Rare Gases :	0.919 % of dry		
Carbone dioxide:	0.033 % of dry		
Total :	100.000 % of dry		
Psychrometric module			
First and second parameters			
Total pressure (Pta)	1013.2500 hPa	[Calculation]	
Temperature (Ta)	15.00 °C		
Third parameter - combustion agent moisture			
<input type="radio"/> Wet bulb temperature (Th,a)	11.92 °C		
<input checked="" type="radio"/> Relative hygrometry (hr,a)	70.000 %	Third parameter maximal value	
<input type="radio"/> Water absolute partial pressure	11.9542 hPa	100.0000	
<input type="radio"/> Absolute hygrometry (h,a)	0.007 kg/kg of dry air		
<input type="radio"/> Dew point temperature (Tr,a)	9.60 °C		
Molar enthalpy (h,a/m)	0.177 kJ/mol of dry air		

Comment about the additional inlet water (Qeadd)

“Qeadd” represents the additional water which is introduced per each unit of fuel quantity, either introduced separately (HAT cycle, some reciprocating engine...) or contained as associated water (associated humidity) in case of liquid or solid fuel (ex in aquazole, orimulsion fuel, or in coal, in wood...).

We note that by definition Qeadd is null in case of traditional systems using gaseous fuel ... But be careful with liquid or solid fuel!

Screen 2D point: Real combustion products data

This screen concerns the 2-D configurations. It means that we know what is the total additional water $Q_{eadd\ sum} = Q_{eaddl} + Q_{eaddv}$ (which is known and null in case of traditional combustion process using gaseous fuel!).

- When $Q_{eadd\ sum} \neq 0$ we must enter the following data to obtain the W+Q value:

Qeaddv (quantity of water in vapour phase input)... kg/kgc or mol/molc of fuel

Real input temperature... °C

Qeaddl (quantity of water in liquid phase input)... kg/kg molc or mol/molc

Real input temperature... °C

- But, if the detail of each phase of the inlet water is not available and indicated, then the W+Q value will can not be displayed!

...

When $Qeadd\ sum = Qeaddl + Qeaddv$ is not known then we can go to the 3-D option (screen n°6) to consider only the gaseous phase of the combustion products. And the 3-D use will let us to obtain $Qeadd\ sum$ in this gaseous phase before (probably) back to the 2-D software option!

Example of screen 2D point

Combustion Hygrometric Diagram - Combustion - 2D point

File Help

Units and reference conditions | Fuel characteristics | Combustion agent characteristics | **2D point** | 3D point | Complement

Do you know the introduced additive water quantity 'Qeadd = Qeadd+' ?

Do you know the detail ? Qeaddl Teaddl
 Qeaddv Teaddv

- If there is no additive water (boiler, ...), you will answer YES
and you will introduce : Qeadd+=0 ; Qeaddl=0 ; Qeaddv=0

If YES, then you obtain all the results,
If NO, you can't be informed about 'W+Q'

YES NO

- If there is liquid water (or condensation), the combustion products
gaseous phase will be saturated ($Tr = Th = Ts = T^* < Trc$).

Additional water :

Qeaddv [mol/molc] Teaddv °C
Qeaddl [mol/molc] Teaddl °C
Qeadd Sum [mol/molc]

Combustion products pressure :

Ptgc hPa

Parameter 1

CO2 [%]
 O2 [%]
 fa
 Ts [°C]
 Th [°C]
 Tr [°C]
 Hpgc (gcv(Te)) [%]

Parameter 2

CO2 [%]
 O2 [%]
 fa
 Ts [°C]
 Th [°C]
 Tr [°C]
 Hpgc (gcv(Te)) [%]

Calculation

THE IMPERATIVE DATA TO ENTER

Ptgc (total pressure of the combustion products) hPa

After we must enter 2 others independent data...

On one side, **as first data** :

Either CO₂ (CO₂ contained in the dry combustion products) %

Or O₂ (O₂ contained in the dry combustion products) %

Or fa (quantity really input of combustion agent related to the stoichiometric quantity)

Or Tr which must be = Tr_c (as calculated dew point temperature corresponding to the total water quantity in the combustion products in the dilution state defined above) °C

On another side, **as second data** :

Either Ts (dry temperature of the combustion products) °C

Or Th (wet bulb temperature of the combustion products) °C

Or Hpc (combustion products enthalpy) %gcv

We also recall that, for a defined Q_{eadd} value, when Th is the second inlet data and as a consequence of the Th definition, there is a one-to-one relationship between Hpc and the couple (X, Th) (X being chosen between CO₂, O₂, fa, Tr_c)*

And, because of the accessibility to Hpc value without requirement of the condensates quantity measurement, it is very important to consider the above relationship in case of condensing exchanger efficiency study.

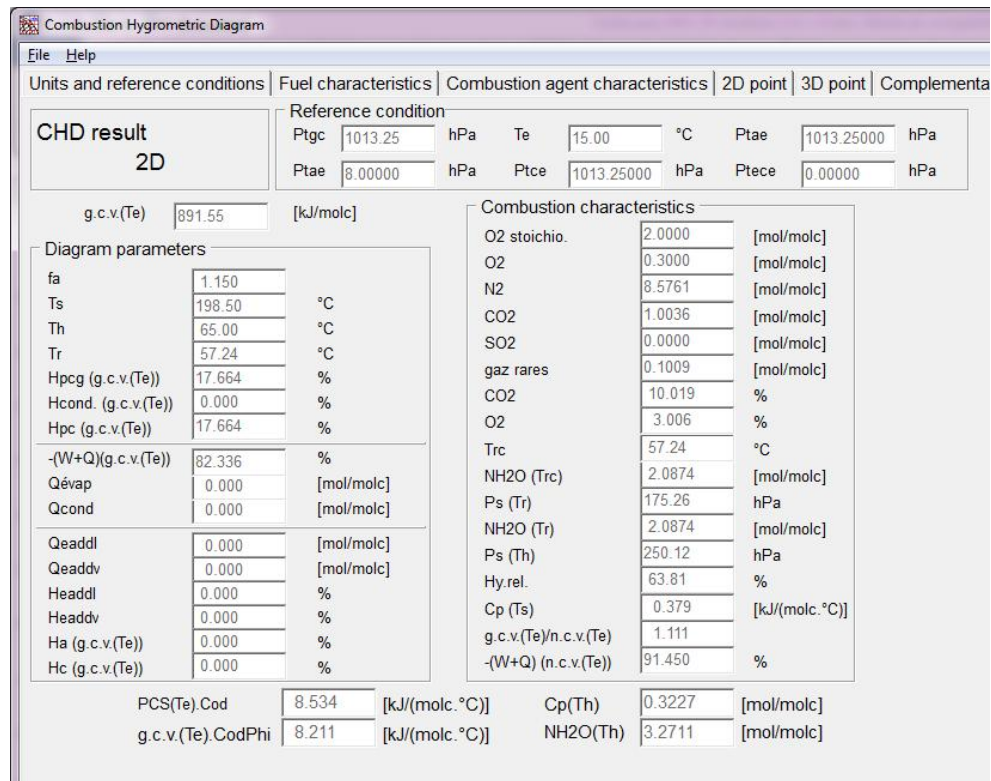
**A more complete explanation is available in the “wet way combustion book”- p 31- or in www.scd.uhp-nancy.fr/docnum/SCD_T_2002_0149_GUILLET.pdf- p.95-*

The available results: we can choose between...

- A point calculation** (screen 2D point)
- A 2-D drawing** (screens Diagram parameters and Diagram plotting)

Screen Results: numerical results of the 2-D option display

Example of screen Results



Examples of CHD 2-D use

- Traditional boiler efficiency research (“traditional” meaning without condensation of the combustion products inside)

A major interest of the CHD software use is to obtain the system efficiency by using only two inlet data... which can be common to measure (as the CO₂, T_s couple) or as the (T_h, T_s) couple, this last couple having the specific advantage to be very cheap (only one thermometer is required!).

Thus, measuring T_s=200°C and T_h= 65.0°C, the above screen indicated that W+Q= 82.24 % gcv(15°C) [we note that the efficiency related to ncv is also displayed by the CHD software, here 91.34 % ncv(15°C)].

- Condensing boiler efficiency research

As already underlined, we recall in the context of condensing process the interest of the T_h measurement...

Thus, for instance, measuring $O_2=3.83\%$ and $Th=40.5^\circ C$, the above screen indicated that $W+Q=94.99\%$ gcv($15^\circ C$) [or 105.50% ncv($15^\circ C$)]

The screen n°5 displays also the Hpc derivatives expressions concerning the saturated gaseous phase of the combustion products as “cod(Th)”, “codPhi(Th)” or “ $N_{H_2O,Th}$ ”, “Cp,Th”). All this data are useful for exchanger sizing following our method.

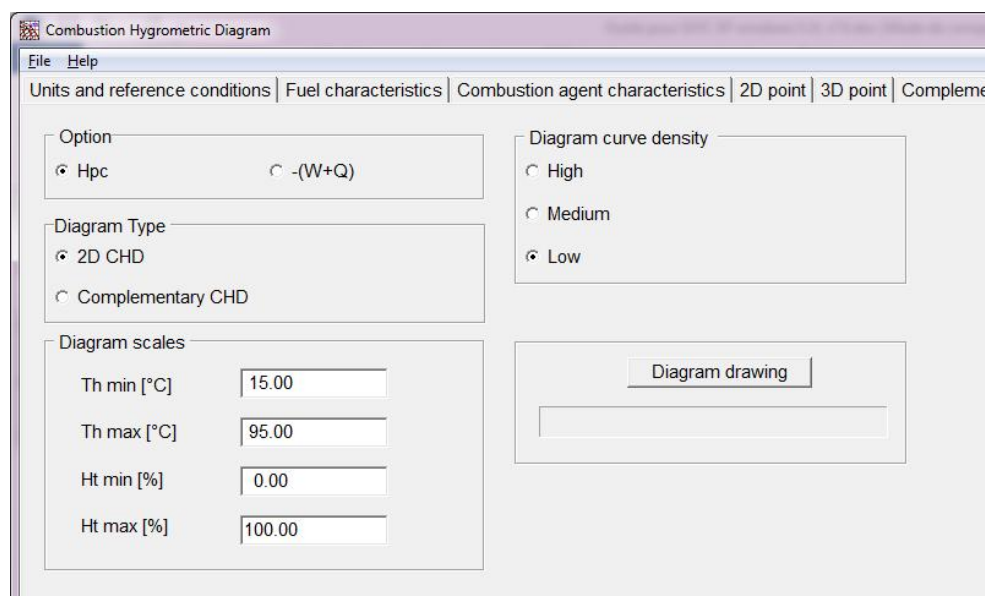
Comment for user

If Tr is a direct measure which is different of Tr_c (with “normally” $Tr < Tr_c$), then it means that there is simultaneously a non-saturated gaseous phase and a “hide” condensation of water inside (we can find these configuration in real exchanger!)

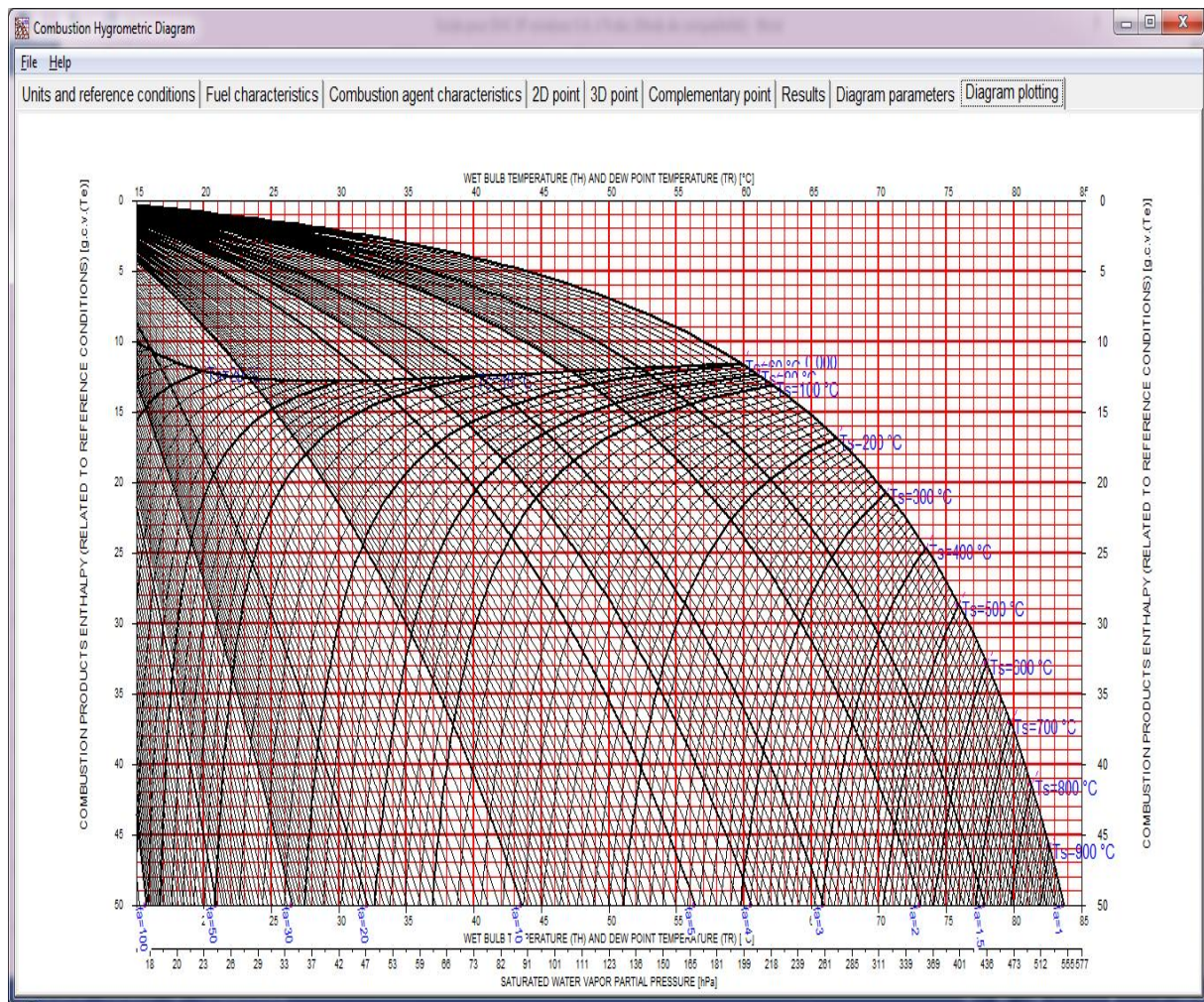
Then, the use of the 3-D diagram helps us to know more about this “hide” condensation (see example further).

Screens *Diagram parameters*

After choosing Th and H_{cp} (or $W+Q$) as major axes we must also define the limit of the drawing.



- Screen *Diagram Plotting* with the main axes are T_h and H_{pc}

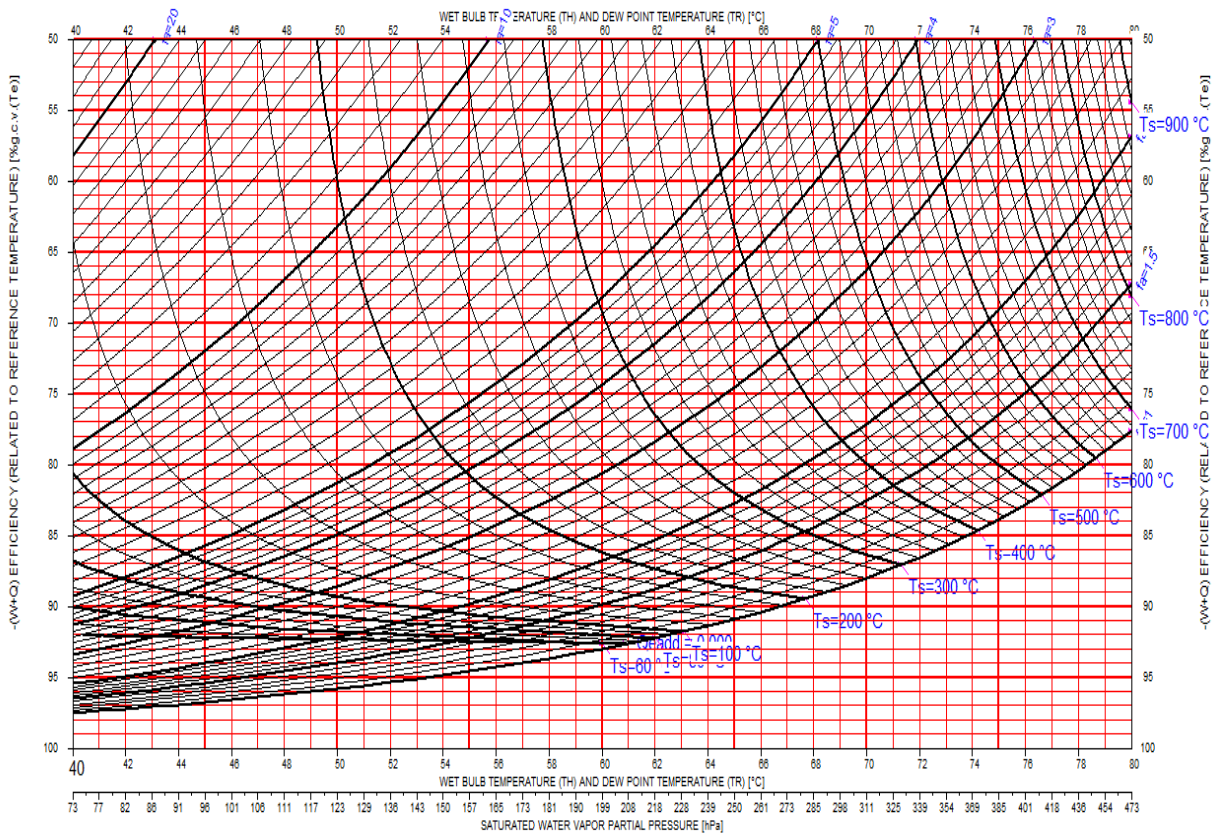


(The above example of 2-D diagram is drawn for a pure methane combustion)

By clicking on the right button of our mouse, an arrow appears on the considered point and all its data are displayed.

-Screen *Diagram plotting* with the main axes are T_h and $W+Q$

This example of 2-D diagram is drawn for a wood combustion (dry wood composition: C=50% of the total dry mass, O=43%, H=7% gcv =45000 kJ/kg of dry wood; the humidity being $Q_{eadd} = 0.4$ kg of H_2O / kg of dry wood)



Screen 3D point

The only combustion products gaseous phase consideration with the “3-D option is often useful when Q_{eadd} sum is not known)... to find it !

For using the 3-D configuration, we must inlet a combination of 3 independent data as (fa, Ts, Th) or (Tr, Ts, Th)...

Example of screen 3D point

Combustion Hygrometric Diagram

File Help

Units and reference conditions | Fuel characteristics | Combustion agent characteristics | 2D point | **3D point** | Complementary point | R

Combustion products pressure :

Ptgc hPa

Calculation

Parameter 1

CO2 [% of dry combustion products]

O2 [% of dry combustion products]

fa

Ts

Th

Tr

Hpgc (gcv(Te)) [%]

Parameter 2

CO2 [% of dry combustion products]

O2 [% of dry combustion products]

fa

Ts [°C]

Th [°C]

Tr [°C]

Hpgc (gcv(Te)) [%]

Parameter 3

CO2 [% of dry combustion products]

O2 [% of dry combustion products]

fa

Ts [°C]

Th [°C]

Tr [°C]

Hpgc (gcv(Te)) [%]

Screen results of the 3-D option display

Example of screen results

Combustion Hygrometric Diagram

File Help

Units and reference conditions | Fuel characteristics | Combustion agent characteristics | 2D point | 3D point | Compl. diag. p

CHD result
3D

Reference condition

Ptgc	1013.25	hPa	Te	15.00	°C	Ptae	1013.25000	hPa
Ptae	8.00000	hPa	Ptce	1013.25000	hPa	Ptece	0.00000	hPa

g.c.v.(Te) 891.55 [kJ/molc]

Diagram parameters

fa	1.150	
Ts	198.50	°C
Th	65.00	°C
Tr	57.24	°C
Hpcg (g.c.v.(Te))	17.665	%
Hcond. (g.c.v.(Te))	-0.000	%
Hpc (g.c.v.(Te))	*****	%
-(W+Q)(g.c.v.(Te))	*****	%
Qévap	0.000	[mol/molc]
Qcond	-0.000	[mol/molc]
Qeaddl	*****	[mol/molc]
Qeaddv	*****	[mol/molc]
Headdl	*****	%
Headdv	*****	%
Ha (g.c.v.(Te))	0.000	%
Hc (g.c.v.(Te))	0.000	%

Combustion characteristics

O2 stoichio.	2.0000	[mol/molc]
O2	0.3000	[mol/molc]
N2	8.5761	[mol/molc]
CO2	1.0036	[mol/molc]
SO2	0.0000	[mol/molc]
gaz rares	0.1009	[mol/molc]
CO2	10.019	%
O2	3.006	%
Trc	57.24	°C
NH2O (Trc)	2.0874	[mol/molc]
Ps (Tr)	175.28	hPa
NH2O (Tr)	2.0877	[mol/molc]
Ps (Th)	250.12	hPa
Hy.rel.	63.82	%
Cp (Ts)	0.379	[kJ/(molc.°C)]
g.c.v.(Te)/n.c.v.(Te)	1.111	
-(W+Q) (n.c.v.(Te))	*****	%

PCS(Te).Cod 8.534 [kJ/(molc.°C)] Cp(Th) 0.3228 [mol/molc]

g.c.v.(Te).CodPhi 8.211 [kJ/(molc.°C)] NH2O(Th) 3.2711 [mol/molc]

As in the 2-D results screen, some Hpc derivatives expressions concerning the saturated gaseous phase of the combustion products appear in this 3-D screen as “cod(Th)”, “codPhi(Th)” or “N_{H2O},Th”, “Cp,Th”, (all data useful for exchanger sizing)

Examples of CHD 3-D use

- Example of Qeadd sum “discovery”

If we are sure that there is no condensation inside... Knowing the state of the (outlet) gaseous phase thanks to 3 independent data we get all the others as Qeadd which is introduced by either separately or by the humid (solid or liquid) fuel...

For example, with a methane combustion and conditions inlet corresponding with the “standard”* conditions, if the measured data are O₂=7.51%; Ts=100°C ; Th=61.6°C, then we find as a result that Qeadd sum = 1.01 mol_{H2O}/molc.

(* $T_c=T_a=15^\circ\text{C}$; $P_{tc}=P_{ta}=1013\text{ hPa}$; $P_{p\text{H}_2\text{O}}=8\text{ hPa}\dots$)

Thus, we can find the water quantity added (here separately)...

Coming back to the 2-D option with $Q_{\text{eadd sum}} = 1.01\text{ mol}_{\text{H}_2\text{O}}/\text{molc}$ and with the couple $\text{O}_2=7.51\%$; $T_h=61.6^\circ\text{C}$, we will find that $W+Q=84.87\%\text{ gcv}(15^\circ\text{C})$.

- Example of confirmation of a suspected water condensation inside

Assuming there is no inlet added water ($Q_{\text{eadd}}=0$)

By using the 3-D option and if we note that T_r in the gaseous phase is different of T_{rc} (calculated value from the fuel and Q_{eadd} values knowledge), then we can prove an “hide” inside condensation... And the condensates quantity is displayed (the Q_{eadd} will be a negative value to mention a condensation).

Thus, the CHD 3-D software appears here as a “hide condensation detector”.

For example (with a methane combustion and conditions corresponding with our standard conditions), we can find that with the measured data in the gaseous phase $\text{CO}_2=8.2\%$; $T_s = 95^\circ\text{C}$; $T_h=46.3^\circ\text{C}$ that in this gaseous phase $Q_{\text{eadd sum}} = - 1.18\text{ mol}_{\text{H}_2\text{O}}/\text{molc}$.

In spite of a non saturated appearance of the gaseous phase the combustion products have condensed a part of the total water vapour “produced”.

To know the efficiency, two way: we can use the 2-D option with $Q_{\text{eadd sum}}=0$ and the couple $\text{CO}_2=8.2\%$; $T_h=46.3^\circ\text{C}$ to find that $W+Q=92.04\%\text{ gcv}(15^\circ\text{C})$.

But we can also use the 2-D option considering that there is a negative inlet $Q_{\text{eaddl}} = -1.18\text{ mol}_{\text{H}_2\text{O}}/\text{molc}$, inlet liquid introduced at the condensates temperature (which will be T_h) to find the same $W+Q$ efficiency value.

Screen *Complementary diagram. point* : the saturated phase of the combustion products (or the “dew surface” consideration)

Thus, the dew surface is developed in the 3-D space. For each point of this surface $T_s=T_h = T_r = T^*$ (As for T_r , the T^* value is indicated by its projection on the T_h axe (see the screen results of the complementary diagram pointing).

On one side of this dew surface the combustion products are oversaturated (with always $T_s = T_h$).

On the other side of this surface, there is no condensates and the combustion products are dry (with always $T_s > T_h$).

As any surface two independent data are enough to plot one point on it.

Example of screen Compl. Diag. point

The complementary CHD inform you about the vapor saturated combustion gases states
In the complementary CHD, $T_r = T_h = T_s = T^*$

Combustion products pressure (Ptgc) : 1013.2500 hPa

Parameter 1

- CO2 [%]
- O2 [%]
- fa
- Qeadd [mol/molc]
- T* [°C]
- Hgcsat. (gcv(Te)) [%]

Parameter 2

- CO2 [%]
- O2 [%]
- fa
- Qeadd [mol/molc]
- T* [°C]
- Hgcsat. (gcv(Te)) [%]

1.150 65.00

Calculation

Screen results of the complementary - option display screen

Example of screen results

CHD result
Complementary

Reference condition

Ptgc	1013.25	hPa	Te	15.00	°C	Ptae	1013.25000	hPa
Ptae	8.00000	hPa	Ptce	1013.25000	hPa	Ptece	0.00000	hPa

g.c.v.(Te) 891.55 [kJ/molc]

Diagram parameters

fa	1.150	
T*	65.00	°C
T*	65.00	°C
T*	65.00	°C
Hpcg (g.c.v.(Te))	18.662	%
Hcond. (g.c.v.(Te))	*****	%
Hpc (g.c.v.(Te))	18.163	%
-(W+Q)(g.c.v.(Te))	*****	%
Qeadd	1.184	[mol/molc]
Qcond	*****	[mol/molc]
Qeaddl	*****	[mol/molc]
Qeaddv	*****	[mol/molc]
Headdl	*****	%
Headdv	*****	%
Ha (g.c.v.(Te))	0.000	%
Hc (g.c.v.(Te))	0.000	%

Combustion characteristics

O2 stoichio.	2.0000	[mol/molc]
O2	0.3000	[mol/molc]
N2	8.5761	[mol/molc]
CO2	1.0036	[mol/molc]
SO2	0.0000	[mol/molc]
gaz rares	0.1009	[mol/molc]
CO2	10.019	%
O2	3.006	%
Trc	*****	°C
NH2O (Trc)	2.0874	[mol/molc]
Ps (Tr)	255.75	hPa
NH2O (Tr)	3.2711	[mol/molc]
Ps (Th)	250.12	hPa
Hy.rel.	103.01	%
Cp (Ts)	0.412	[kJ/(molc.°C)]
g.c.v.(Te)/n.c.v.(Te)	1.111	
-(W+Q) (n.c.v.(Te))	*****	%

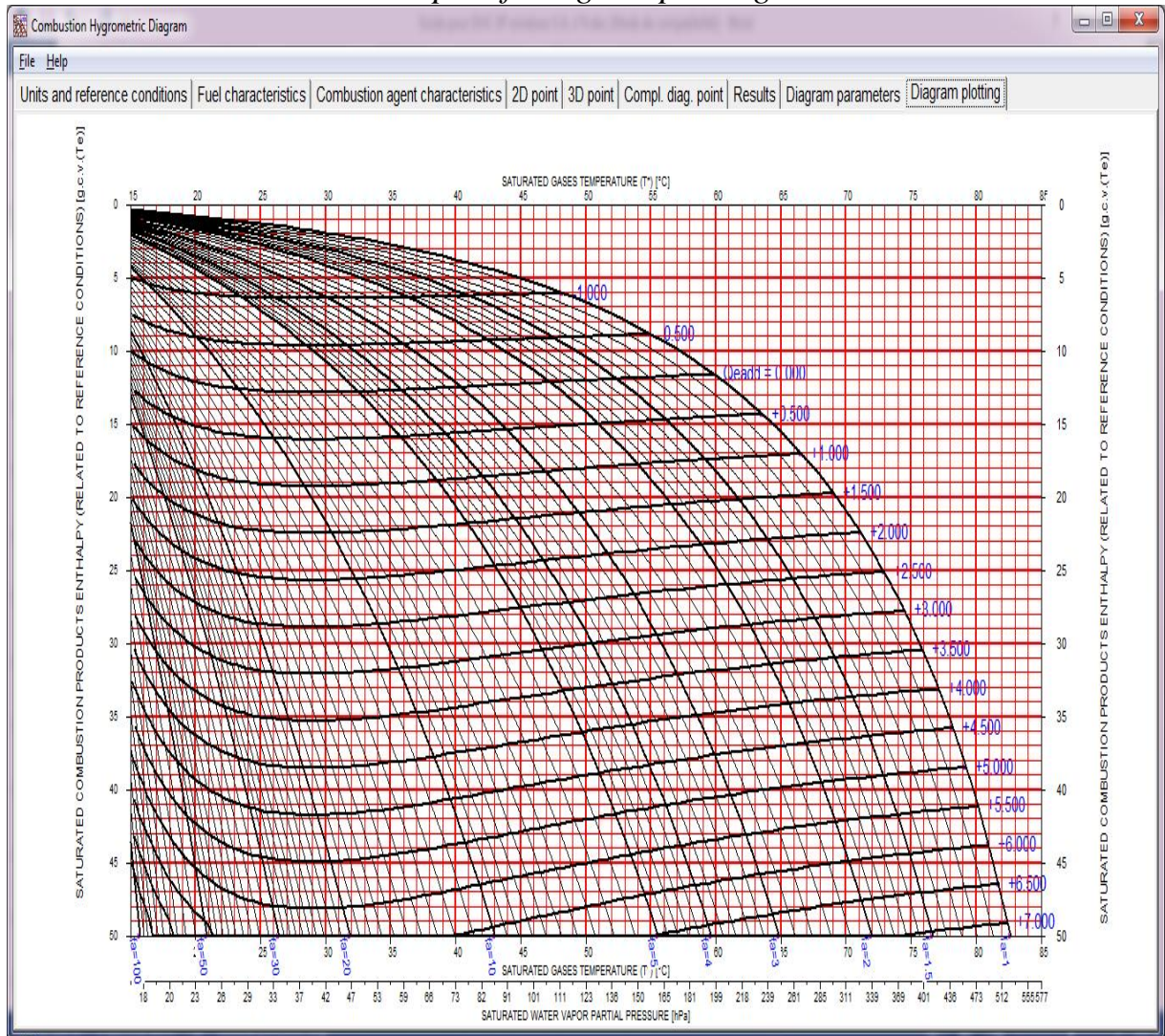
PCS(Te).Cod	9.354	[kJ/(molc.°C)]	Cp(T*)	0.4116	[mol/molc]
g.c.v.(Te).CodPhi	8.942	[kJ/(molc.°C)]	NH2O(T*)	3.2711	[mol/molc]

The parameters as codPhi , C_p ... appear also (here attached to the T^* values).

Screen *Diagram plotting* for the complementary diagram

When the dew point surface is projected on the T_h / H_{pc} plan following the Q_{add} axe, we obtain the complementary diagram...

Example of Diagram plotting



And because it is a representation of the dew point surface, the complementary diagram is a relevant tool for water vapour pump efficiency analysis, for bi-phase exchangers sizing anticipation...

Other examples of CHD applications

After the combustion systems analysis, the humidity in fuel, inside hide condensation detection, the CHD help us to anticipate the efficiency of many cycles, as STIG (Steam In Gas Turbines) or HAT (Humidified Air Turbines), of water vapour pump cycles, help us to anticipate the atmospheric condensation (water vapour plume formation) and eliminate it, help us to anticipate the sizing of bi-phase exchangers...

More explanations are provided in “Wet Way Combustion” book (by Rémi Guillet / Elsevier ed. 2000 p. 52 to 64* or in the Rémi Guillet thesis “La combustion par voie humide et ses performances” and free available at:

www.scd.uhp-nancy.fr/docnum/SCD_T_2002_0149_GUILLET.pdf

* also provided in the CHD software *tool guide version* - see the “appendix”

- CHD and Gas turbine cycles

As example, considering a HAT (Humidified Air Turbine) cycle and knowing the compression rate (for example=10), the compression air temperature (for example=342°C), the CHD helps us to find the couple (fa, Qeadd) to maximize the W efficiency when the temperature at the expander inlet is limited at 1000°C, the temperature after expanding is 530°C to find:
fa= 4.1 ; Qeadd= 6.7 mol_{H2O}/molc) and W = 44.1 % gcv(15°C)...

- CHD and water vapour pump efficiency

A process and its associated condenser equipped with a water vapour pump is equivalent to a system without water vapour pump, but now exhausting its combustion products at a lower enthalpy level than before (decreasing following the enthalpy recycled by the water vapour pump and re-cycled by the inlet combustion air)...

Thus, we can use the C.H.D. diagram to easily (graphically) anticipate the efficiency of a “water vapour pump” exchange. And, generally ignoring what is exactly the water vapour quantity in the combustion products, we will use the C.H.D. 2D complementary-diagram to anticipate all the water vapour pump parameters.

- CHD and atmospheric plume

After the inside condensation detection and assuming that the exhaust fumes temperature is the result of a convection exchange between the outlet fumes and atmospheric air, the CHD tool let us to anticipate the atmospheric plume formation (with a final risk of black ice on the ground in cold countries !) and to eliminate it !

And to do this anticipation we will use a 2-D diagram drawn when the reference for enthalpies calculation are the real atmospheric conditions...

- CHD and bi-phases exchangers sizing

The derivatives expressions dH / dT_H and dN_{H_2O}/dT_H useful to get the « cod » and “cod phi” values used in the humid exchanger sizing and efficiency anticipation (following the method we suggest for bi-phase exchangers) are provided by the CHD...

More about the CHD...

The choice of parameters

The CHD software is also the base of a new metrology due to a strong interest in the wet bulb temperature knowledge.

Since the fuel composition is rarely known with a good precision but only by the fuel “family” affiliation (for instance, natural gas family, LPG...) CHD takes account of the outstanding stabilities of many dimensionless parameters (inside a same fuel family).

It is to benefit of such properties that the enthalpies are always expressed relating to the fuel calorific power, that the air factor is chosen to draw diagrams...

More explanation about these “stabilities” and the accuracy of the CHD method are provided in “Wet Way Combustion” book (by Rémi Guillet / Elsevier ed. 2000 **p. 65 to 71***) or in the Rémi Guillet thesis “La combustion par voie humide et ses performances” p. 129 to 138 and free available at:

[www.scd.uhp-nancy.fr/docnum/SCD T 2002 0149 GUILLET.pdf](http://www.scd.uhp-nancy.fr/docnum/SCD_T_2002_0149_GUILLET.pdf)

* also provided in the CHD software *tool guide version* - see the “appendix”