# Carbon dioxide geothermal loop for energy and heat production

# Operation in Gas, liquid and critical phases

May 2020

CONTENT

# 1_Introduction

A lot of energy is available into the ground. Heat is currently recovered by conventional geothermal production systems extracting hot water stored at large depth. In most cases, water is available at medium temperature (between 50 to 100 °C depending on depth and reservoir characteristics) which is sufficiently high to provide heating to residential areas. In other cases, water pressure and temperature are considerably greater providing high pressure steam together with hot water. In these cases, energy may be recovered at the surface through a steam turbine. Following treatment, water is disposed at the surface or re-injected into the ground depending on water properties and local regulation.

Carbon dioxide is detrimental to the environment. As a consequence, this gas is occasionally injected into the ground for long time storage.

Carbon dioxide storage and heat available into the ground are two parameters that have to be considered for energy supply. This could be performed by using a geothermal loop where the gas is extracted from a storage cavity, energy and heat recovered at the surface then the gas re-injected into the ground. Operating such a system with any gas would not provide necessarily any benefit when the energy required to re-inject the gas may be more or less equivalent to the energy recovered at the surface.

Carbon dioxide thermodynamic properties may be used to provide a positive energy balance as it is shown in this document.

# 2_Description of the system

The system consists in a carbon dioxide geothermal loop including at ground surface a gas expander and cooling devices, a liquid (or super critical) injection well and a production well supplying a hot pressurised gas to the expander. In between the two wells, carbon dioxide is stored in a high pressure and high temperature reservoir.

Following gas cooling (below 30 °C) downstream the expander, carbon dioxide is either in a liquid or a super critical phase (dense) condition characterized by a very large volumetric mass (approximately 1000 kg/m3). The fluid is discharged, through the injection well, into the high pressure and high temperature reservoir where heat is progressively transferred to the newly injected fluid.

Production and injection wells are sufficiently remote in order that the newly injected carbon dioxide mass does not reach the production well in a too short time therefore at a temperature lower than the reservoir temperature.

Carbon dioxide is supplied by the production well at a high temperature (for instance 150 °C) in a gas phase condition with a medium volumetric mass (for instance 500 kg/m3).

Considering the difference in volumetric masses, the pressure at the production well is significantly greater than the one at the injection well, the difference in pressures increasing with the well length and the reservoir temperature. This difference in pressure may be used to activate an expander transmitting energy to a load: an electric generator or a mechanical machine (compressor or pump).

In the event that the cooling provided by the gas expansion is not sufficient to reach liquid condition required for carbon dioxide injection, the gas is further cooled down in one or several external cooling devices (designated below by Post cooling). Some options of cooling means are mentioned below.

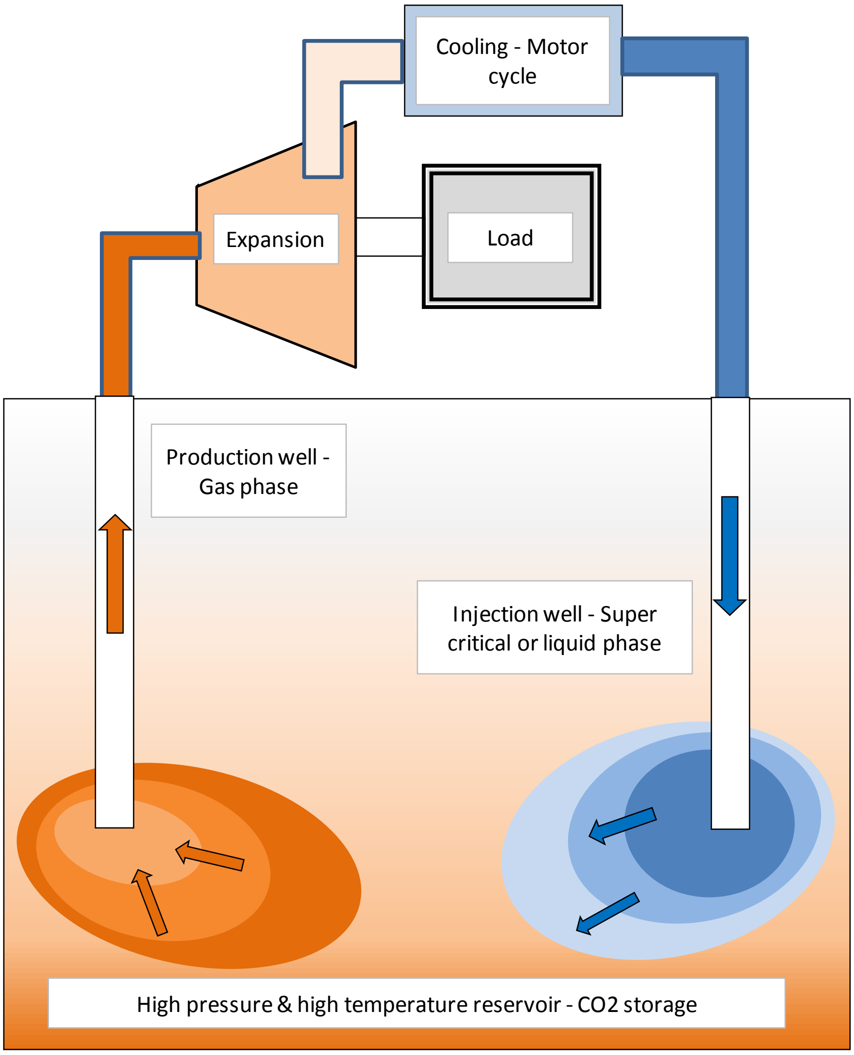



*Figure 2 – Schematic of the carbon dioxide geothermal loop.*

# 3_ Reservoir characteristics

An indication of reservoir temperature is given by:

[https://www.sciencedirect.com/topics/engineering/reservoir-temperature](https://www.sciencedirect.com/topics/engineering/reservoir-temperature).

According to this document, the reservoir temperature could be estimated by adding the surface temperature to a **temperature gradient ranging from 0.5 °C (minimum) to 0.9 °C (maximum) per 30 m.** This gradient would be valid for most reservoirs. However, there are anomalies where this gradient may be considerably larger. It is not said in this document, if the temperature of the surface differs significantly to the reservoir temperature. This may be an important comment considering the gas expansion (according an isentropic process) occurring during its displacement from the reservoir to the surface (pressure varying with the manometric head of the fluid).

As a first indication, reservoir pressure is related to the manometric head of water.

Based on a value of 0.9 °C per 30 m, reservoir temperatures and pressures for a depth ranging from 1000 to 5000 m would be approximately the following:

| Depth - meters | Temperature - °C | Pressure - Bar |
|---|---|---|
| 1000 | 49 | 100 |
| 2000 | 78 | 200 |
| 3000 | 107 | 300 |
| 4000 | 137 | 400 |
| 5000 | 166 | 500 |

According to: https://en.wikipedia.org/wiki/Petroleum_reservoir; organic elements buried in depths of 1000 to 6000 m present a temperature ranging from 60 to 150 °C.

According to: https://petrowiki.org/Reservoir_pressure_and_temperature; Reservoir temperature is governed primarily by the reservoir's proximity to the earth's mantle and by the relative heat exchange capacities and thermal conductivities of the formations forming the lithostatic sequence that includes the reservoir.

The geothermal gradient resulting from the heat-exchange process varies from basin to basin, but within a specific area the variations are small. In most hydrocarbon-producing areas, the gradient is usually in the range of 0.6 to 1.6°F per 100 ft of depth increase. Areas where the earth's crust is thinner than average, such as volcanic and geothermal areas, have much higher gradients. In thin-crust areas the gradient change averages 4°F per 100 ft of depth increase. Local temperature gradients at depth have been reported as high as 10°F per 100 ft approaching singularities (e.g., major faults, areas of tectonic movement) in the earth's crust in geothermal areas.

Converted into metric units, **4°F per 100ft** represents 7.3°C per 100 m (93°C at 1 000 m and 384°C at 5 000 m by considering a surface temperature of 20°C). **10°F per 100ft** represents 18.2°C per 100 m (202°C at 1 000 m and 931°C at 5 000 m by considering a surface temperature of 20°C).

According to: https://link.springer.com/article/10.1007/s13202-016-0275-1 "Investigation of reservoir temperature in a gas reservoir in Middle East: case study"; the temperature would be 260 °F at 11 000 ft representing a temperature gradient of **1.8°F per 100 ft** that is **33 °C per 1 000 m**.

The field of **Elgin – Franklin** https://fr.wikipedia.org/wiki/Elgin-Franklin_(gisement) is usually called « HP/HT » that is "High Pressure and High Temperature" due to its uncommon reservoir characteristics. The reservoir depth is 6 100 m while the temperature exceeds, in some parts, 200 °C and the pressure is of the order of 1 150 bar.

# 4_ Carbon dioxide thermodynamic properties

Carbon dioxide thermodynamic properties may be presented on a Mollier diagram providing pressure variation versus enthalpy for several temperature conditions. On this diagram, entropy and specific volume lines are also usually represented. The following Mollier diagram was obtained from http://frederic.benet.free.fr/ website.

The carbon dioxide geothermal loop operates under the following thermodynamic conditions:

- The gas is firstly extracted from a reservoir through a production well at a relatively high pressure and high temperature condition. As the gas rises in the production well, the pressure is reduced and the gas is expanded with little friction losses due to the low gas velocity in the pipe. In that case, **the expansion in the production well is isentropic** (constant entropy). The gas expansion is accompanied by a temperature reduction.
- At the surface, the gas is expanded in a turbine (an expander) providing mechanical energy to a load (electric generator or mechanical drive). The gas expansion is carried out with some losses during the turbine crossing (not quite an isentropic process). This process is irreversible and characterised by a **polytropic efficiency** slightly lower than 1. Gas expansion in that turbine is also accompanied by a temperature reduction.
- Before its re injection, the fluid is cooled down at constant (or relatively) pressure. This is an **isobaric process**. Following the cooling process, the fluid is in a liquid or a super critical condition (intermediate between gas and liquid condition).
- Following cooling, the fluid with a very high volumetric mass is re injected into the reservoir. As the fluid flows down, the pressure rises due to the monometric head represented by the fluid column (weight of the fluid) without a significant change in the fluid temperature. This is an **isothermal process**.
- In the reservoir, the fluid flows slowly from the injection to the production wells receiving heat from the ambient media. Disregarding the losses caused by the fluid entrance into and exit from the reservoir, the pressure is relatively constant. This is an **isobaric process.**

**Carbon dioxide hydrate** or **carbon dioxide clathrate** is a snow-like crystalline substance composed of water ice and carbon dioxide. It is normally a Type I gas clathrate. The clathrate formation occurs below approximately 283K (10 C). See https://en.wikipedia.org/wiki/Carbon_dioxide_clathrate.

It is therefore important not to operate the geothermal loop and more particularly the injection well below 10 °C in order to avoid the formation of carbon dioxide hydrates and therefore the plugging of the injection well.

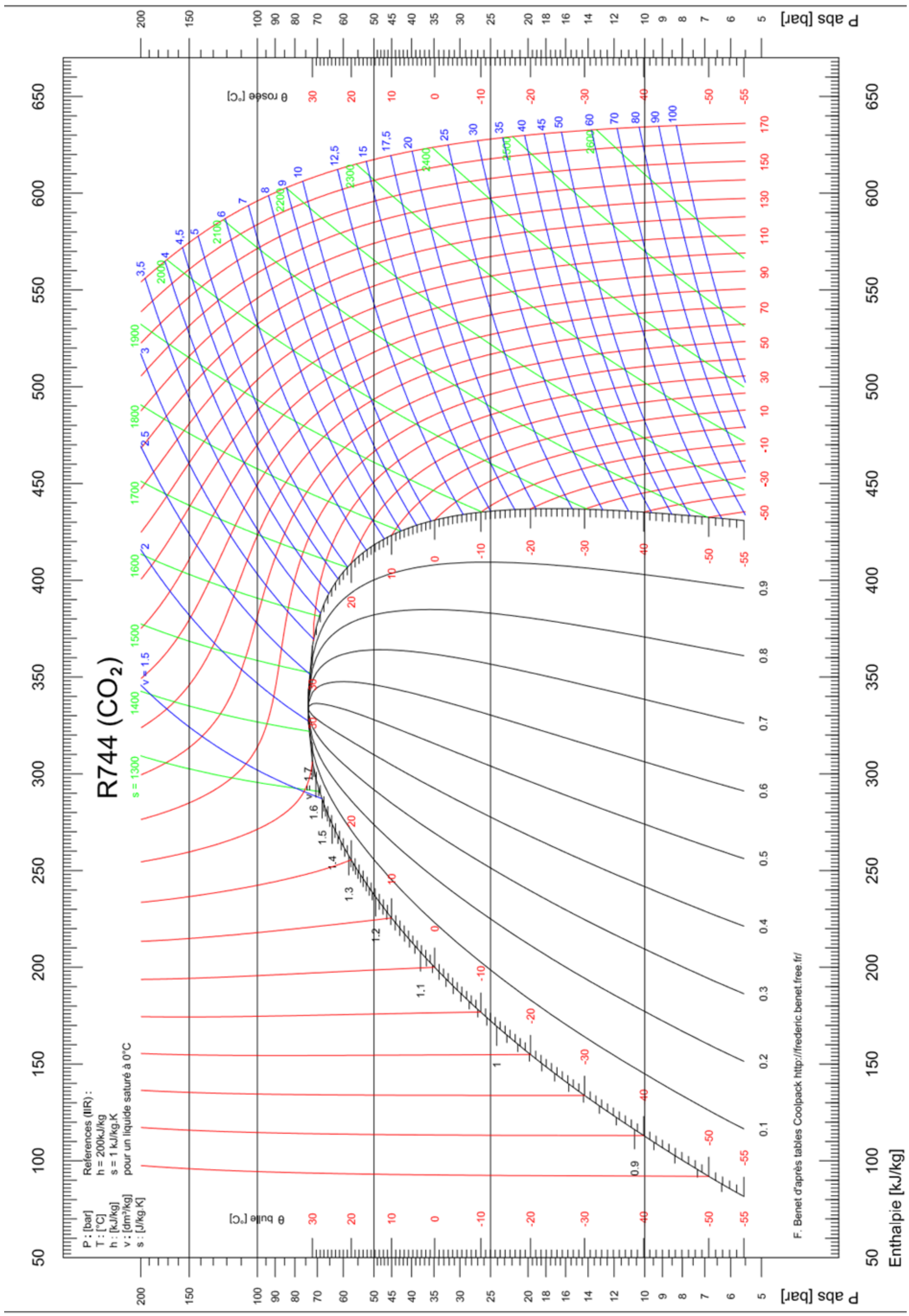



*Figure 3 – Carbon dioxide thermodynamic properties – Mollier diagram*

# 5_ Example of geothermal loop

A geothermal loop was studied based on the following operating conditions:

- Reservoir pressure and temperature, respectively, 319 bar abs and 180 °C. This is analysed in section 6.5.
- Injection and production well length: 2 750 m. This is analysed in section 6.3.
- Injection and production well diameter, respectively, 150 mm and 250 mm. This is analysed in section 6.4.
- Carbon dioxide mass flow rate: 100 kg/s. This is analysed in section 6.4.
- Expander isentropic efficiency: 85 %. This is commented in section 6.4.
- Expander discharge pressure: 80 bar abs. This is analysed in section 6.2.
- Gas cooling before injection into the reservoir: 10°C which is also the limit for hydrate formation. This is analysed in section 6.1 (Post expansion cooling).

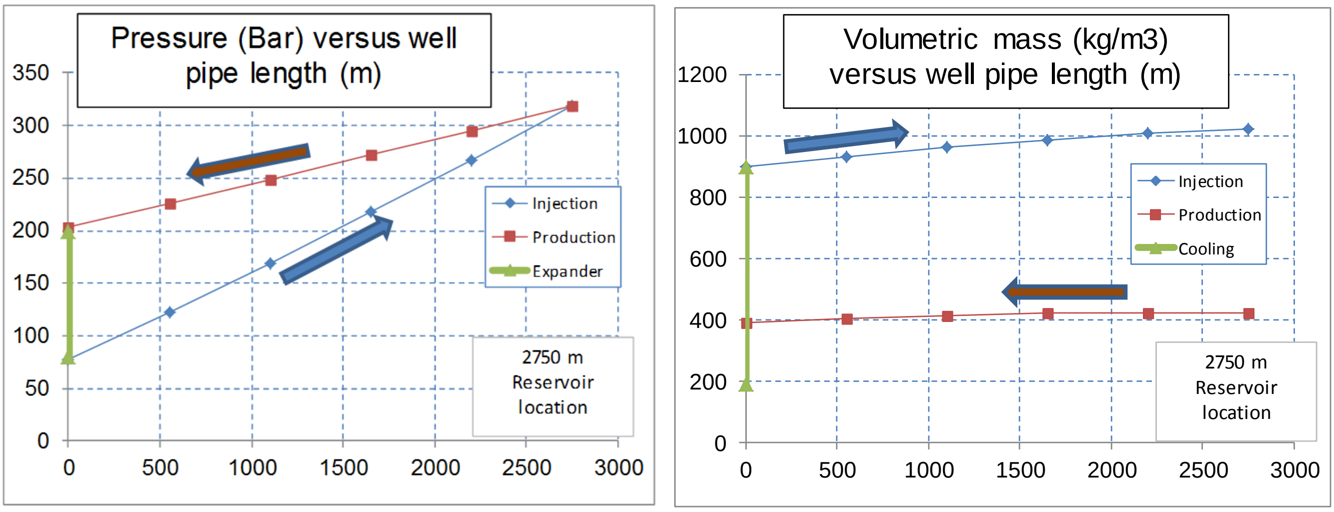



*Figure 5.1.a and b – Pressure and volumetric mass along injection and production well pipes.*

Carbon dioxide exits the reservoir with a pressure of 319 bar abs and a temperature of 180°C. Due to the fluid manometric head (weight of the column of fluid), the gas reaches the surface with a pressure of 203 bar abs. Due to gas expansion in the production well (pressure decrease), the temperature at the surface reduces down to 135°C. See figures 5.1.a and b. As an average, the gas volumetric mass in the production well is of the order of 400 kg/m3.

Through the expander, the gas is cooled down to 62 °C (57.6 °C for an isentropic expansion) then cooled in a final step by an external fluid down to 10°C. This provides a volumetric mass of 900 kg/m3 at the injection wellhead and of the order of 1000 kg/m3 at the bottom of the well. This results in a wellhead pressure of 78 bar abs i.e. 2 bars below the expander outlet pressure.

An isentropic expansion of the gas entering the expander with a pressure of 199 bar abs and a temperature of 135 °C and exiting it with a pressure of 80 bar abs provides an energy unit of 43.2 kJ/kg (power unit of 43.2 kW for a mass flow rate of 1 kg/s). The energy unit corresponds to an enthalpy difference of 498.1 kJ/kg (entrance) and 454.9 kJ/kg (exit). Calculating the actual expansion work with an isentropic factor of 1.3; entrance and exit compressibility factors of, respectively, 0.662 and 0.657; a molecular weight of 44 provide an energy unit value of 41.8 kJ/kg, very close to the enthalpy calculation. In this calculation case, the entropy is equal to 1.820 kJ/kg°K.

Applying an isentropic efficiency of 85 %, it results that the energy provided by the expander is 36.7 kJ/kg (36.7 kW power unit).

The heating rate dissipated during the final cooling process is 236 kW for a mass flow rate of 1 kg/s. The total heating rate transmitted by the reservoir to the gas is 273 kW the expander delivering only 13.4 % of that power.

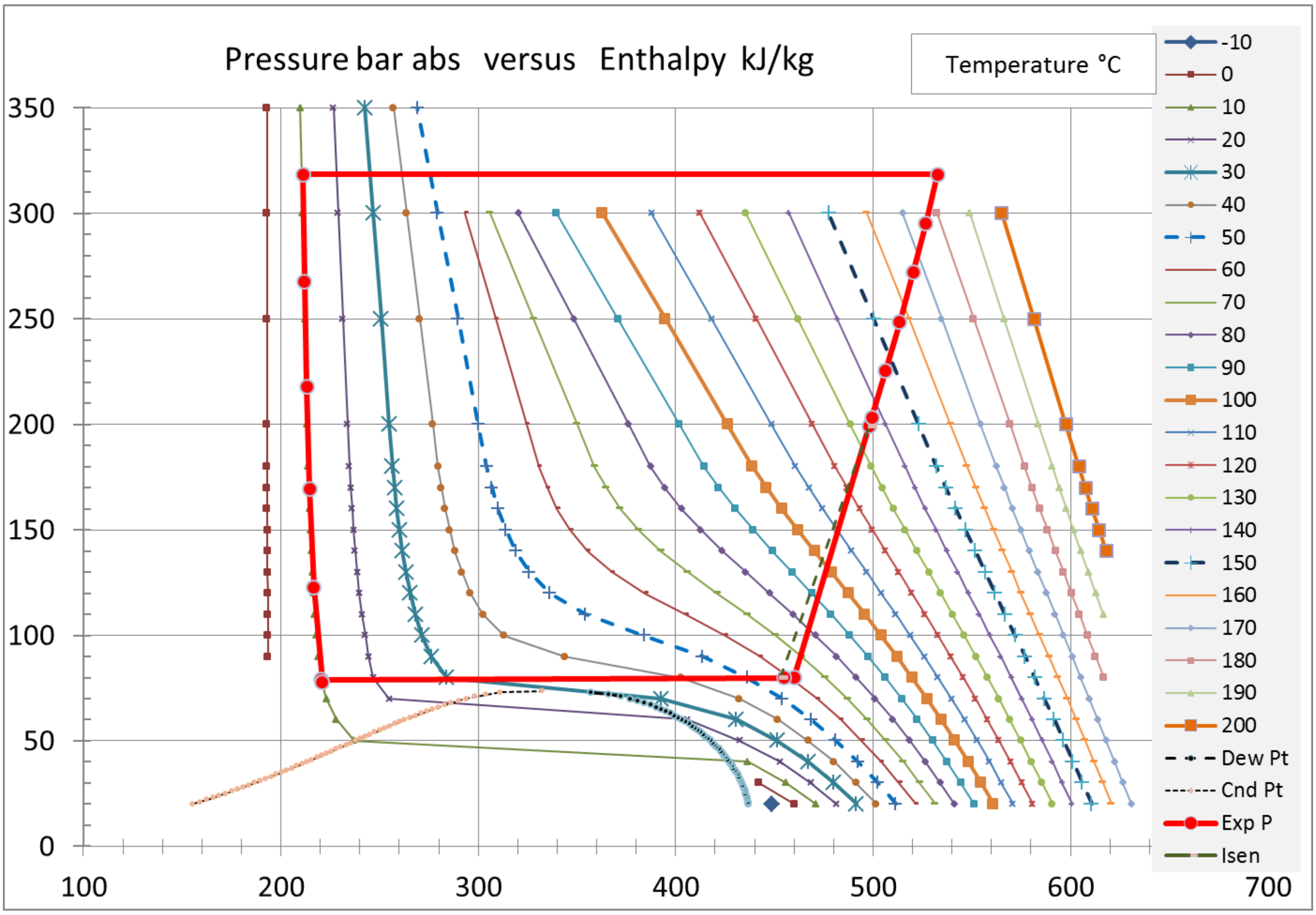



*Figure 5.2 – Pressure versus enthalpy with temperature lines – Geothermal loop (In red) represented on a CO2 Mollier diagram*

# 6_ Parameter analysis

## 6.1_ Post expansion cooling

Calculation has been carried out to determine the effect of the post cooling i.e. the temperature at the injection wellhead on the geothermal loop. This calculation has been performed for 10, 20 and 30 °C.

In a general manner, the volumetric mass decreases in both the injection and the production well. This provides some sort of compensating effect: the volumetric mass reduction in the injection well reduces locally the manometric head (therefore the "corresponding reservoir pressure") while the volumetric mass reduction in the production well reduces locally the manometric head permitting a lower reduction in the production wellhead pressure. See figures 6.1.a and b also 6.2.a and b.

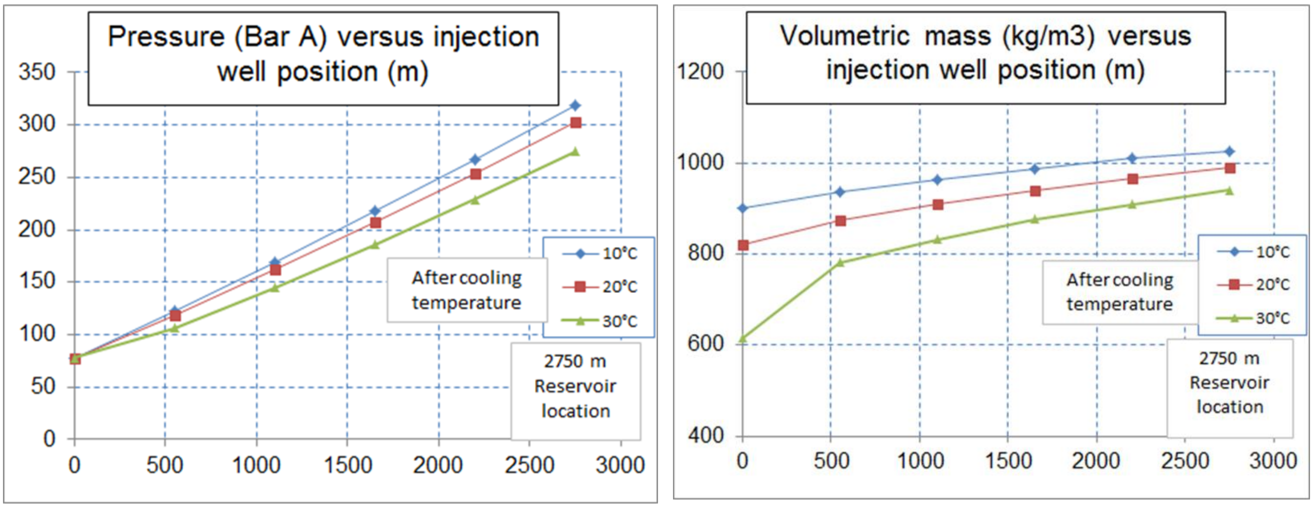



*Figure 6.1.a and b – Pressure and volumetric mass along injection well pipe for three cooling temperature values at the wellhead.*

The difference in performance is relatively small for post cooling temperatures of 10 and 20°C. In that instance, the production wellhead pressure is only reduced from 203 to 191 bar and the expansion pressure ratio in the expander only reduced from 1 / 2.54 to 1 / 2.39.

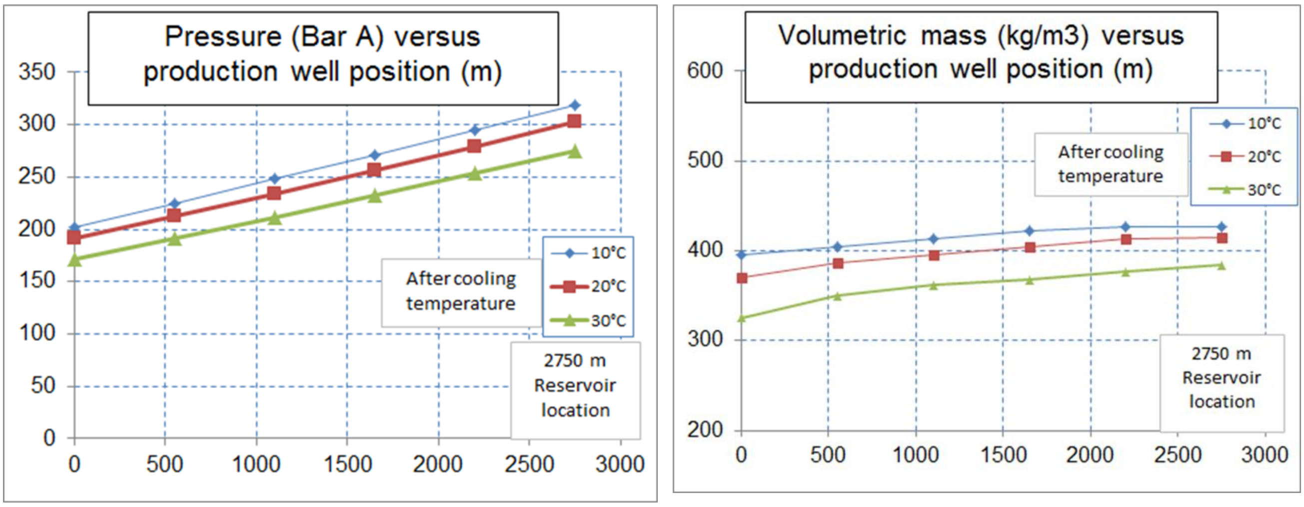



*Figure 6.2.a and b – Pressure and volumetric mass along production well pipe for three cooling temperature values – Wellhead entrance.*

The effect of the post cooling becomes important above 20°C, particularly in the lower pressure sections of the injection and production well pipes. See the change in volumetric mass near the surface in the two wells. When the post cooling temperature is increased from 20 to 30°C, the expansion pressure ratio in the expander is reduced from 1 / 2.39 to 1 / 2.15. This corresponds to a significant power supply reduction in the expander.

| Post cooling temperature | 10°C | 20°C | 30°C |
|---|---|---|---|
| Isentropic work kJ/kg – 1 kg/s | 45.1 | 42.2 | 37.4 |
| Expander outlet temperature °C | 57.6 | 61.6 | 69.9 |
| Work reduction relative to 10°C | 0 % | 6.4 % | 17.1 % |

*Table 6.1 – Work supplied by the expander for 3 wellhead temperatures (10 to 30 °C). No pressure loss assumed between production wellhead and inlet expnder.*

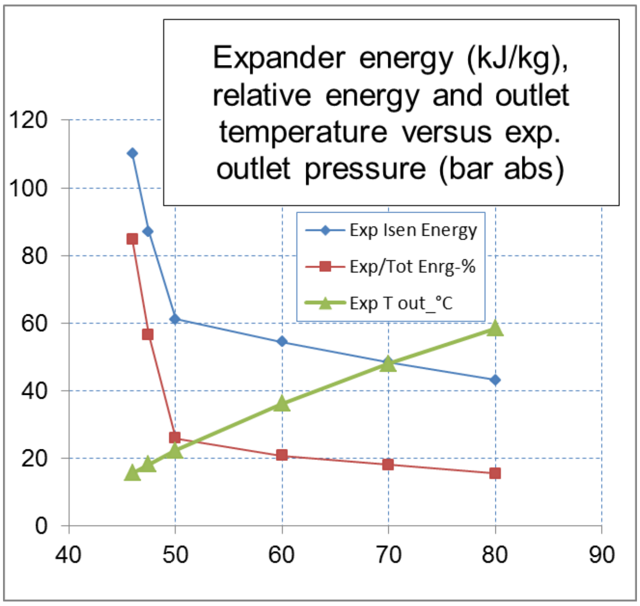
The post cooling may be provided in several manners:

- Heat at hot temperature may be supplied to residential areas if any in the vicinity.
- Heat at hot temperature may be used to activate a motor cycle. See section 7.
- Heat at medium temperature may be supplied to residential areas by using heat pumps.
- Heat at medium temperature may be disposed by using a local cooling media (water from the sea or a river or from the ambient air.)

## 6.2_ Expander outlet pressure

The case analysed in section 5 refers to an expander outlet pressure of 80 bar abs. This parameter was diminished to analyse its effect down to 46 bar where it approaches the dew point line. It has to be noted that this calculation was performed keeping constant the expander inlet conditions (199 bar abs and 135 °C).

By reducing this parameter from 80 bar, the energy per unit mass delivered by the expander increases significantly. The variation is relatively linear down to 60 bar below which the variation is quasi exponential.



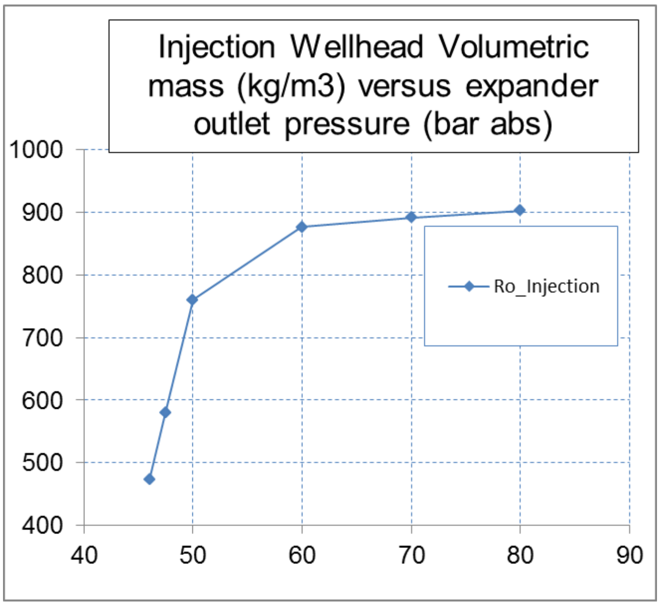




*Figure 6.3.a and b – Expander isentropic energy and expander / total energy ratio (left); Injection wellhead volumetric mass (right) versus expander outlet pressure (Bar abs).*

The pressure at the injection wellhead decreases as the expander outlet pressure reduces. It is relatively small down to 60 bar becoming relatively important below that value. It is quasi exponential below 50 bar compromising the operation of the geothermal loop.

To get the exact performance of the geothermal loop an integrated calculation (expander, cooling, injection and production wells) needs to be performed for each expander outlet pressure condition.

## 6.3_ Well pipe length

To evaluate the impact on the expander energy supply, injection and production pipe lengths have been increased by 20 % (from 2 750 to 3 300 m) keeping the reservoir temperature unchanged. Note that this parameter should normally be varied with the reservoir pressure.

The pipe length being greater, the manometric head in the injection well is also greater. Taking into account the pressure losses into the pipe, the differential pressure (reservoir minus surface) is increased by 21 % (from 240 bar to 291 bar, respectively, for the 2 750 and the 3 300 m length).

The pipe length and the fluid volumetric mass (greater reservoir pressure) being both greater, the manometric head in the production well is considerably increased. The differential pressure (reservoir minus surface) is increased by 34 % (from 115 to 155 bar) while the differential temperature is increased by 19 % (from 44.8 to 53.5 °C) due to gas expansion from the reservoir to the surface.

At the expander inlet, the temperature is reduced from 135 (2 750 m) to 126.5°C (3 300 m).while the pressure ratio is increased from 1 / 2.49 to 1 / 2.63. As a consequence, the expander energy supply is increased by 14 %.

An approximate law may be proposed around the 2 750 m length with the present assumptions:

**Energy increased in fraction = (Length increased in fraction) ^ (0.71)**

## 6.4_ Loop mass flow rate

Calculation in section 5 has been performed on the basis of a mass flow rate of 100 kg/s but could be extended to any mass flow rate following some adaptation of the equipment to the actual mass flow rate and applying for some corrections, particularly, concerning energy losses. The geothermal performance has been analysed regarding the loop sizing.

It has to be noted that:

- Listed pipe diameter values do not correspond to standard sizes (just indicative). Values have been selected to meet fluid velocity requirement and to ease the comparison between the three flow cases listed below.
- Post expansion cooling is considered below from 59.5 to 10°C (enthalpy reduced from 457 to 221 kJ/kg) that is with an enthalpy reduction of 236 kJ/kg. If it was considered from 60 to 30°C (enthalpy reduced from 457 and 295 kJ/kg) the enthalpy reduction would be 162 kJ/kg that is 69 % of the previous value. Note that the temperature reduction in the second case is only 60 % of the first case.

For a **100 kg/s mass flow rate**, the equipment requirement do not present major constraints (150 and 250 mm pipe diameter for injection and production wells), however, the power provided by the expander is relatively small (isentropic 4.32 MW). The residual heat (post cooling) may present some advantage if exploited. Otherwise, it may rather be considered as a disadvantage due to the equipment required.

For a **1 000 kg/s mass flow rate** (4 000 m3/hr at the injection wellhead), the power provided by the expander is significant (isentropic 44 MW) and the pipe diameters are still of a reasonable diameter (475 and 790 mm in this calculation). Again the post cooling of the gas may present an advantage or a disadvantage depending on its potential use and on the equipment required.

For a **10 000 kg/s mass flow rate**, the power provided by the expander is quite important (isentropic 460 MW), the cooling duty is also hugged (2.36 GW) as the equivalent pipe diameters (2.5 m diameter for the production well if there were only one pipe). This case could become realistic when the reservoir is of relatively large dimension and could sustain the pressure for a long time duration by considering several injection and production wells located at a large distance from each other. This configuration could be of a great interest in a large urban area considering the amount of energy available, particularly, heating capability (size of two nuclear power plants).

In the three above cases, pipe diameters have been selected particularly large in order to minimize the pressure losses in the injection and production wells. If the injection well diameter was reduced by 20 %, the corresponding reservoir pressure would be reduced by 10 % and the column differential pressure by 14 %. This diameter reduction has therefore to be considered as an extreme limit. If the production well diameter was reduced by 30 %, the corresponding wellhead pressure would be reduced by 6 % and the column differential pressure would be increased by 9 %. This diameter reduction has also to be considered as an extreme limit.

Beyond these diameter reductions, the operation of the geothermal loop would be compromised.

| **Mass flow rate kg/s** | **100** | **1 000** | **10 000** |
|---|---|---|---|
| Injection wellhead - Volume flow m3/s and m3/hr | 0.1111 & 400 | 1.111 & 4 000 | 11.11 & 40 000 |
| Expander efficiency | 0.85 | 0.85 to 0.90 | 0.90 |
| Actual expand. power - MW | 3.67 | 37.8 | 388 |
| Injection pipe dia - mm | 150 | 475 | 1500 |
| Inject. WH-Gas velocity, m/s | 6.29 | 6.27 | 6.29 |
| Production pipe dia - mm | 250 | 790 | 2500 |
| Prod. WH-Gas velocity, m/s | 4.77 | 4.78 | 4.77 |
| Post expansion gas cooling 59.5 to 10°C | 23.6 | 236 | 2 360 |

*Table 6.4 – Parameter variation with the flow rate. In these three cases, volumetric mass is 900 kg/m3 at injection wellhead and 400 kg/m3 at production wellhead.*

## 6.5_ Reservoir temperature

The calculation has been performed in two cases of reservoir temperature (180 and 150 °C) keeping constant the expander pressure ratio (approx. 1 / 2.48).

Despite the expander pressure ratio was kept approximately constant, the power supplied by the expander is considerably reduced: 19.9 MW instead of 36.7 MW (46 % less) by reducing the reservoir temperature from 180 to 150°C.

| **Reservoir temperature °C** | **180** | **150** |
|---|---|---|
| Reservoir pressure – Bar abs | 318 | 305 |
| Injection W.head press – Bar A and column pressure - Bar | 78 and 240 | 66.5 and 238 |
| Production W.head press – Bar A and column pressure - Bar | 203 and 115 | 171 and 134 |
| Production W.head temperature and expansion cooling – °C | 135 and 45 | 97 and 53 |
| Expander in & out pressure bar abs and ratio | 199 and 80 Ratio 1 / 2.49 | 170 and 68.5 Ratio 1 / 2.48 |
| Expander energy – kJ/kg | 36.7 actual & 43.2 isentropic | 19.9 actual & 23.4 isentropic |
| Expander inlet and outlet temperature - °C | 135 and 58.5 | 97.5 and 36 |
| Expander inlet and outlet volumetric mass – kg/m3 | 390 and 195 | 422 and 374 |
| Post cooling – kJ/kg | 23.6 | 18.6 |
| Energy / Post cooling ratio - % | 13.4 | 9.6 |

*Table 6.5 – Two cases of reservoir temperature with constant expander pressure ratio..*

**This highlights the importance of a reservoir with a hot temperature.**

# 7_ Secondary circuit

Section 5 indicates that energy of 43.2 kJ/kg and residual heat of 236 kJ/kg may be extracted for every mass unit of produced carbon dioxide. These two figures correspond, respectively, to 43.2 kW (expander delivered power) and 236 kW (heat power) for a flow rate of 1 kg/s.

It has to be recalled that these figures are obtained for inlet and outlet pressures, of respectively, 199 and 80 bar abs and an inlet temperature of 135°C (“HT” on figure 7.1). Based on an isentropic efficiency of 85 %, the outlet temperature is 62 °C (“MHT” on figure 7.1). The residual heat is therefore available at this last temperature.

The process fluid needs to be considerably cooled down in order to be efficiently re injected into the storage reservoir. It has been shown in section 6.1 that the efficiency of the geothermal loop is reduced by 6.4 % by increasing the injection temperature from 10 °C to 20 °C (17 % in the case of 30 °C).

It is assumed in the following that a cooling media is available at a relatively low temperature. Then the two heat sources at a different temperature may be used to activate a motor cycle (also called below the "Secondary circuit"). The efficiency of the motor cycle is dependent on the temperature difference. The following table indicates the Carnot efficiency corresponding to a hot source at 60 °C and a cold source with a temperature spreading between 30 and minus 6.8 °C.

| Cold source temperature | Carnot efficiency |
|---|---|
| 30 °C | 9.0 % |
| 20 °C | 12.0 % |
| 10 °C | 15.0 % |
| 6.8 °C | 16.0 % |
| 0 °C | 18.0 % |
| Minus 6.8 °C | 20.0 % |

*Table 7.1 - Carnot efficiency based on a 60 °C hot source*

The motor cycle includes conventionally an evaporator, an expander, a pump, a condenser, and a refrigerant fluid flowing in that order (evaporator to expander, condenser and pump). Into the evaporator, the refrigerant removes heat from the main fluid entering at a temperature of 60 °C. Operating the motor cycle at a relatively high pressure (80 bar in the present case) the refrigerant fluid (gas phase) is sent towards the expander where the gas expansion produces energy and some cooling of the gas. At its outlet, the gas enters into the condenser where it is cooled by an external media transforming it into a liquid phase. At the condenser outlet, the liquid is pressurised at the evaporator operating pressure level to initiate another refrigerant cycle. The heating received by the refrigerant into the evaporator converts it again into a gas phase.

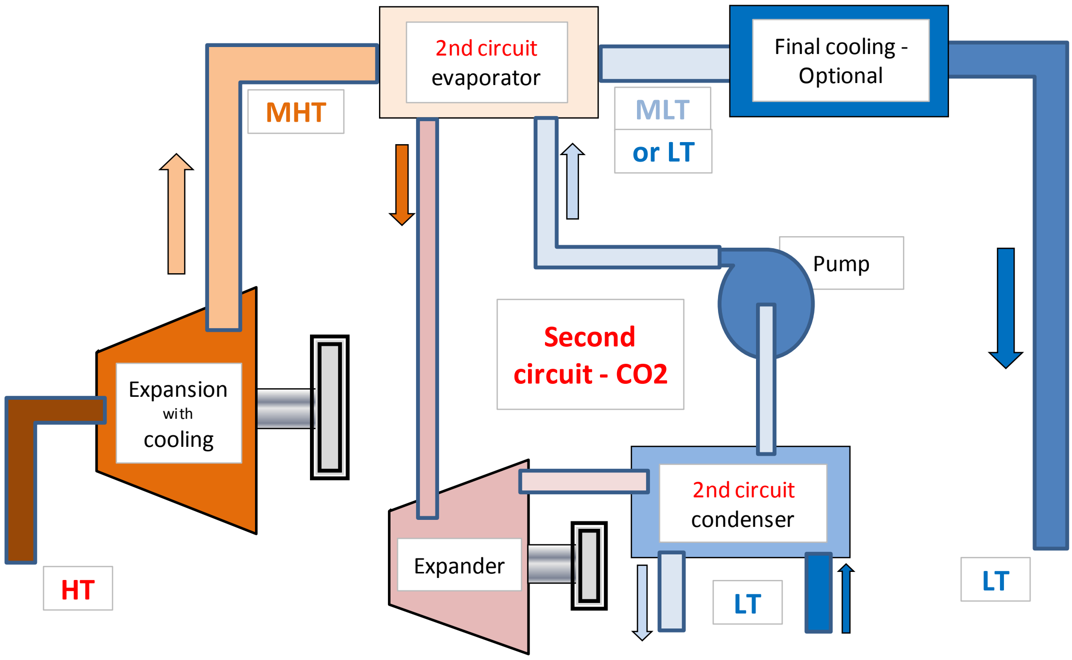



*Figure 7.1 – Schematic of the secondary circuit for additional energy production.*

### Cooling media between 10 and 20 °C

Temperature at this level may be encountered in many circumstances: atmospheric air, aquifers, water from the sea surface (cold or temperate seas) or pumped from the thermocline in the case of tropical seas.

Calculations have not been performed in that temperature range but some order of magnitude may be deduced from the table above (Carnot efficiency versus cold temperature) and the two calculations below performed at two low temperatures: plus 6.8 and minus 6.8°C. It has to be noted that the Carnot efficiency is relatively proportional to the hot and cold temperature difference.

Calculations below have been performed using the CoolPack software developed by the Department of Mechanical Engineering (MEK), Section of Thermal Energy (TES) at the Technical University of Denmark (DTU).

### Cooling media at plus 6.8 °C

The cycle has to be operated with pure carbon dioxide in order to avoid the formation of hydrates at a temperature lower than 10°C.

The expander operates with inlet pressure and temperature of, respectively, 80 bar abs and 60°C and an outlet pressure of 40 bar abs. This last pressure value was selected in relation with the corresponding expander outlet temperature (6.9°C) very close to the dew point line.

Main results are presented in table 7.2.a. Following expansion of the main fluid under conditions mentioned in section 5, 236 kJ/kg needs to be removed, based on a flow rate of 1 kg/s in order to cool down the main fluid from 60 to 10 °C.

| | | | |
|---|---|---|---|
| Main expander energy | - 43.2 kJ/kg | Heat available | 236 kJ/kg |
| 2$^{nd}$ circuit expander enrg | - 26.6 kJ/kg | Carnot efficiency | 16.0 % |
| 2$^{nd}$ circuit pump energy | 4.44 kJ/kg | Cycle efficiency | 9.3 % |
| 2$^{nd}$ circuit total recovery | - 22,1 kJ/kg | 2$^{nd}$ Crct/Main Power % | 51 % |

*Table 7.2.a – Overall performance based on a 6.8 °C cooling at the condenser of the secondary circuit.*

The secondary circuit absorbs most of the heat available from the main fluid through the evaporator while the expander supplies 26.6 kJ/kg (actually 22.0 kJ/kg if we consider that 4.5 kJ/kg are required to pump the liquid refrigerant from 40 to 80 bar abs) and releases the rest of the heat through the condenser.

The calculation was performed with a cooling temperature of 6.8 °C. This has an important consequence: an extra cooling system is required or the cooling is permitted only under a reduced period of time (seasonal conditions). This could be the case in the North Sea where the sea temperature is often close to 4°C

The study has been performed only with pure carbon dioxide. Other refrigerant fluids could be investigated to evaluate their respective benefit.

### Cooling media at minus 6.8 °C

As commented above, the cycle has to be operated with pure carbon dioxide. This severe cooling condition may only be encountered for a short period of time (operation in winter in some areas). This case is considered to provide an indication of the performance variation and also because the expander outlet operates in two phase flow.

The expander operates with inlet pressure and temperature of, respectively, 80 bar abs and 60°C and an outlet pressure of 33 bar abs.

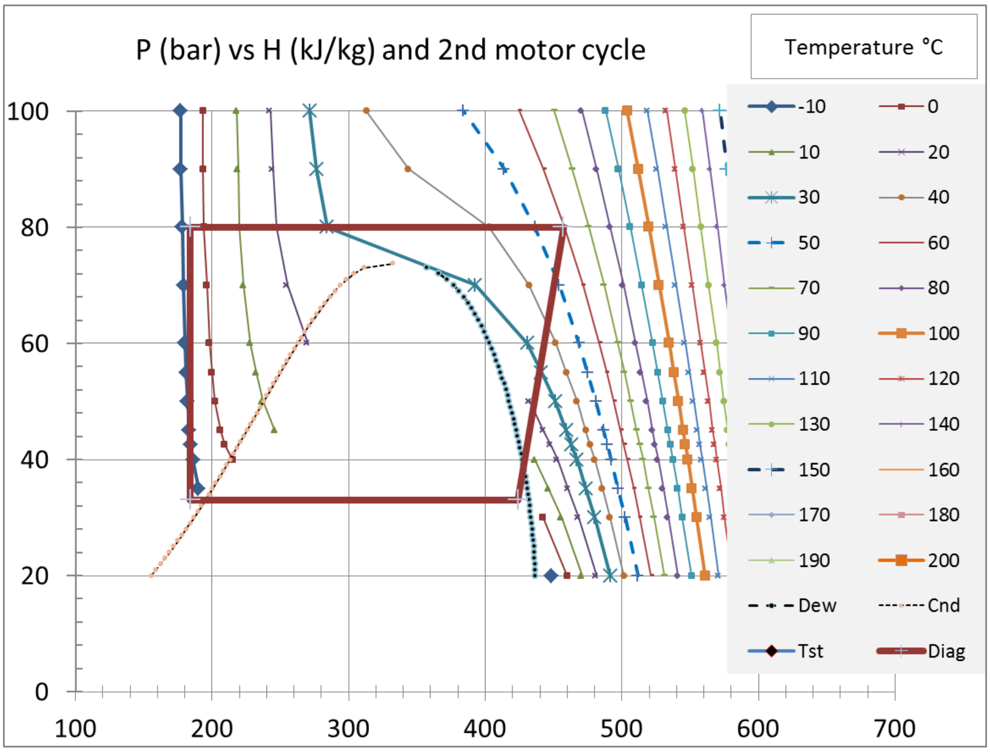



*Figure 7.2 – Pressure – Enthalpy CO2 diagram with representation of the motor cycle operating with pure CO2. Cycle operation down to minus 6.8 °C.*

Main results are presented in table 7.2.b. Following expansion of the main fluid under conditions mentioned in section 5, 236 kJ/kg may to be removed based on a flow rate of 1 kg/s in order to cool down the main fluid from 60 to 10 °C.

| | | | |
|---|---|---|---|
| Main expander | - 43.2 kJ/kg | Heat available | 236 kJ/kg |
| 2nd circuit expander | 33.3 kJ/kg | Carnot efficiency | 20.0 % |
| 2nd circuit pump | 4.84 kJ/kg | Cycle efficiency | 12.0 % |
| 2nd circuit recovery | - 28.5 kJ/kg | 2nd Crc./Main Power | 66 % |

*Table 7.2.b - Overall performance based on a minus 6.8 °C cooling at the condenser of the secondary circuit.*

The secondary circuit absorbs most of the heat available from the main fluid through the evaporator while the expander supplies 33.3 kJ/kg (actually 28.5 kJ/kg if we consider that 4.8 kJ/kg are required to pump the liquid refrigerant from 33 to 80 bar abs) and releases the rest of the heat through the condenser.

Same comment is made as before concerning the severe condition of cooling to achieve this performance. Same comment is also made concerning the potential benefit of another refrigerant.

# 8_ Merging main and secondary circuits

Depending on a large number of parameters:

- Reservoir temperature and pressure.
- Reservoir depth and volume
- Risk of formation of hydrates in the main circuit
- Characteristics of the cold source

In some circumstances, it may be simpler to operate the geothermal loop with a single expander and with a pure refrigerant with adapted characteristics. This could be the case for instance, when the pressure difference between the two wells is small, the reservoir can provide a large amount of heat at medium temperature and when the temperature of the cold source is relatively low. This is typically the case where the energy of the main expander is significantly lower than the one of the secondary circuit.

That point may be looked at in the future.

# 9_ Conclusion

A geothermal loop may be operated with carbon dioxide without any pressurizing equipment. To the contrary, **a geothermal loop may produce mechanical energy** when site conditions are present. This energy is accompanied with a significant amount of heat at a relatively high temperature.

The large difference in manometric heads between the injection well, characterized by a large volumetric mass of the falling fluid (liquid of the order of 1 000 kg/m3) and the production well, characterized by a medium volumetric mass of the rising fluid (gas of the order of 400 kg/m3) permits the operation of a geothermal loop due to the existence of a large pressure difference between the two wells. A sufficiently long residential time of the carbon dioxide (or a large distance between the wells) is required to permit sufficient heat exchange in the reservoir between the newly injected and the stored fluids.

**The efficiency of the geothermal loop increases with the reservoir temperature, the reservoir pressure and the well length**. This indicates that only specific areas are suitable for producing heat and energy in an efficient way. If only heat is required, the application field of the technology is considerably wider.

Calculations in different reservoir configurations indicate that **10 to 15 % of the capted reservoir heat may be converted into mechanical energy**. More than 15 % of energy could be produced with higher reservoir temperature, pressure and depth.

The **residual heat** may be used to provide **heating to residential areas** if they are present in close vicinity. If it is not the case, a fraction of that heat may be converted to mechanical energy in a **second motor cycle circuit**, the evaporator of this circuit absorbing the heat available at the outlet of the main expander. The efficiency of that loop is of the order of 10 % (approximately 50 to 60 % of the Carnot efficiency). The operation of the second circuit was analysed with pure carbon dioxide operating at low temperature (around 0°C, only available in specific areas or for reduced time intervals). It is possible that this second circuit would operate more efficiently with another refrigerant. This may be tested in a near future.

As an overall, the main geothermal loop and the second motor cycle circuit may convert 15 to 20% of the capted heat into mechanical energy.

# Appendix – CO2 thermodynamic properties

Data plotted in graph below were obtained from Ohio University web site : https://www.ohio.edu/mechanical/thermo/property_tables/co2/

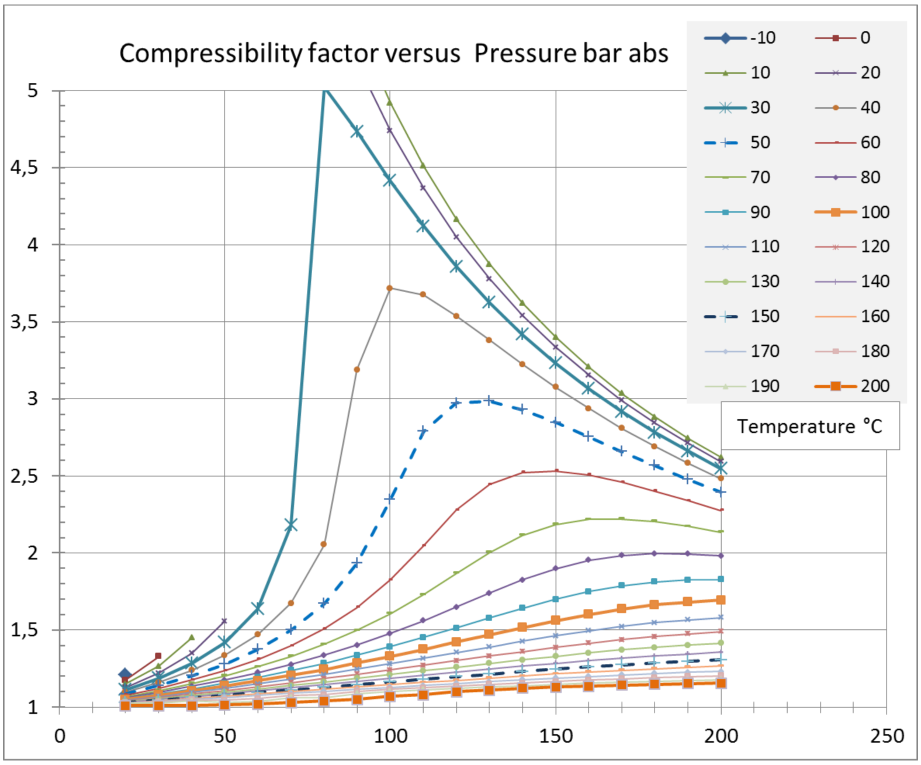



*Figure A1 – Compressibility factor versus pressure (abscissa) and temperature*

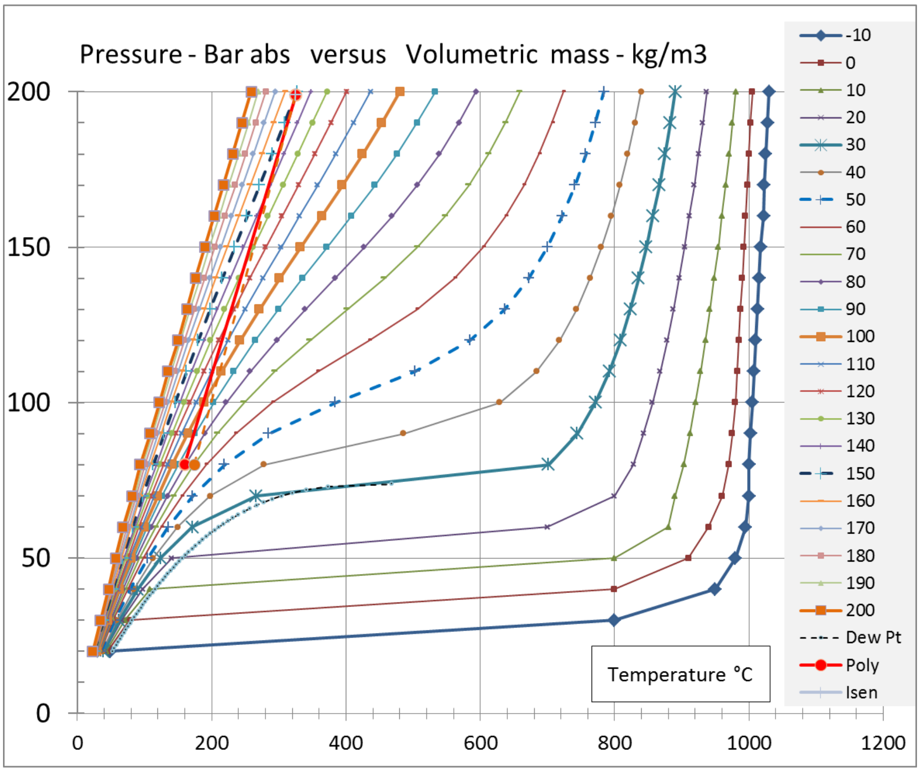



*Figure A2 – Pressure versus volumetric mass (abscissa) and temperature*

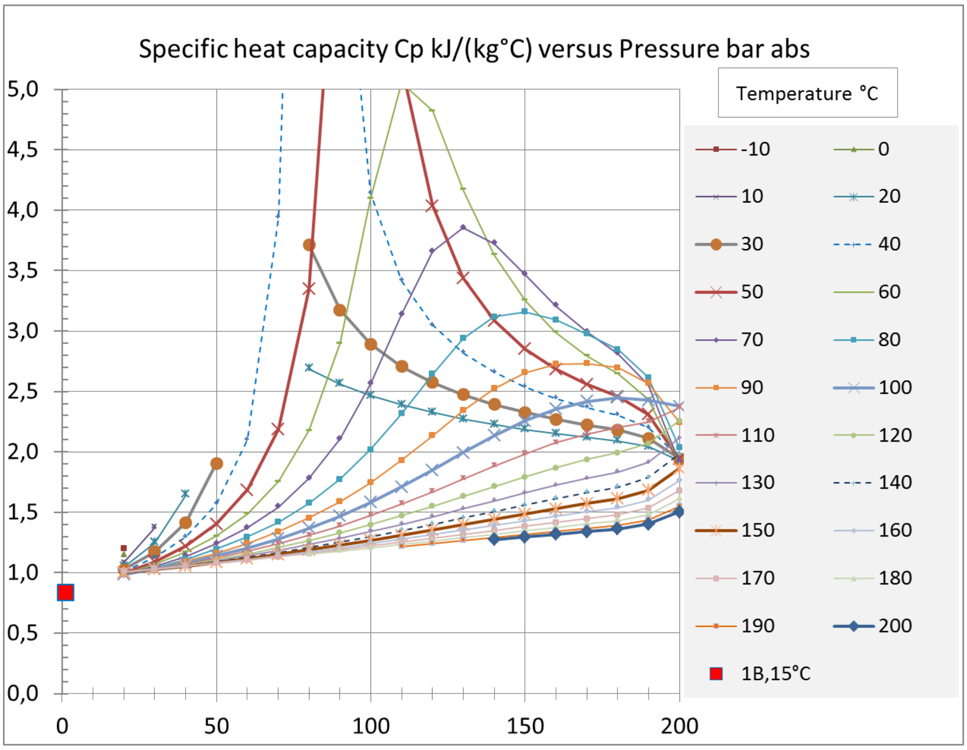



*Figure A3 – Specific heat vs pressure (abscissa) and temperature – Square: 1 Bar abs; 15 °C*

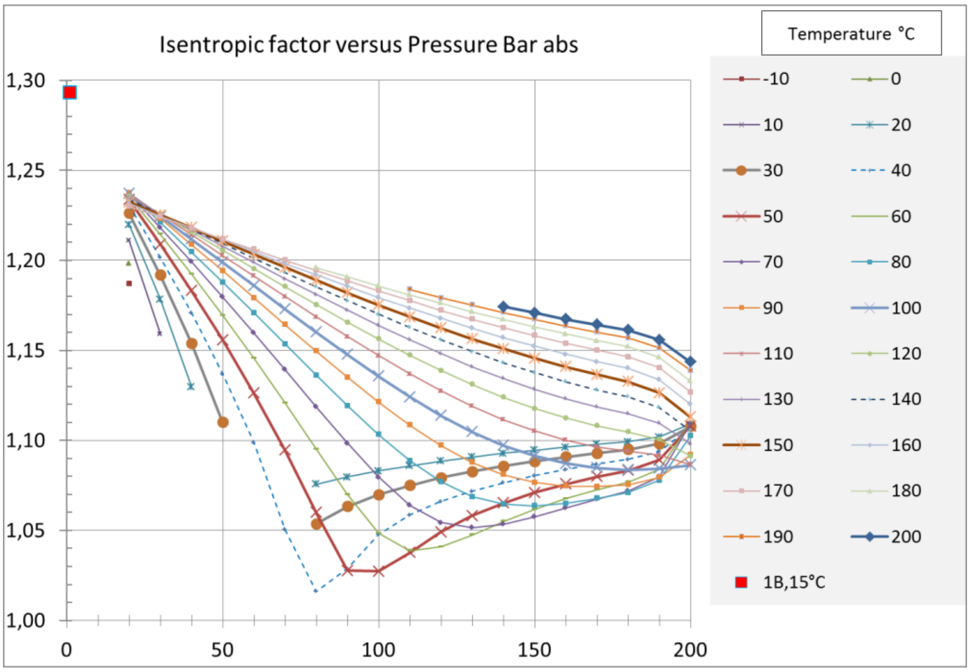



*Figure A4 – Isentropic factor (indicative) vs pressure and temperature – Square: 1 Bar abs; 15 °C*

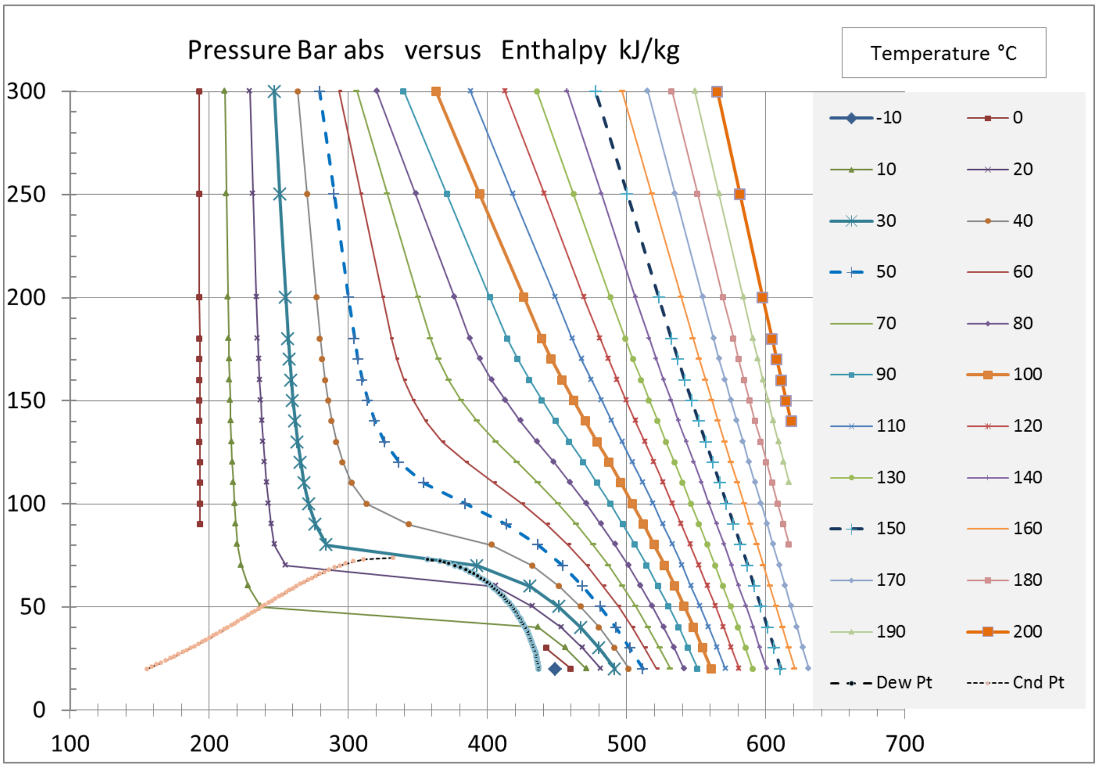



*Figure A5 – Pressure versus enthalpy (abscissa) and temperature lines with dew and condensation lines*

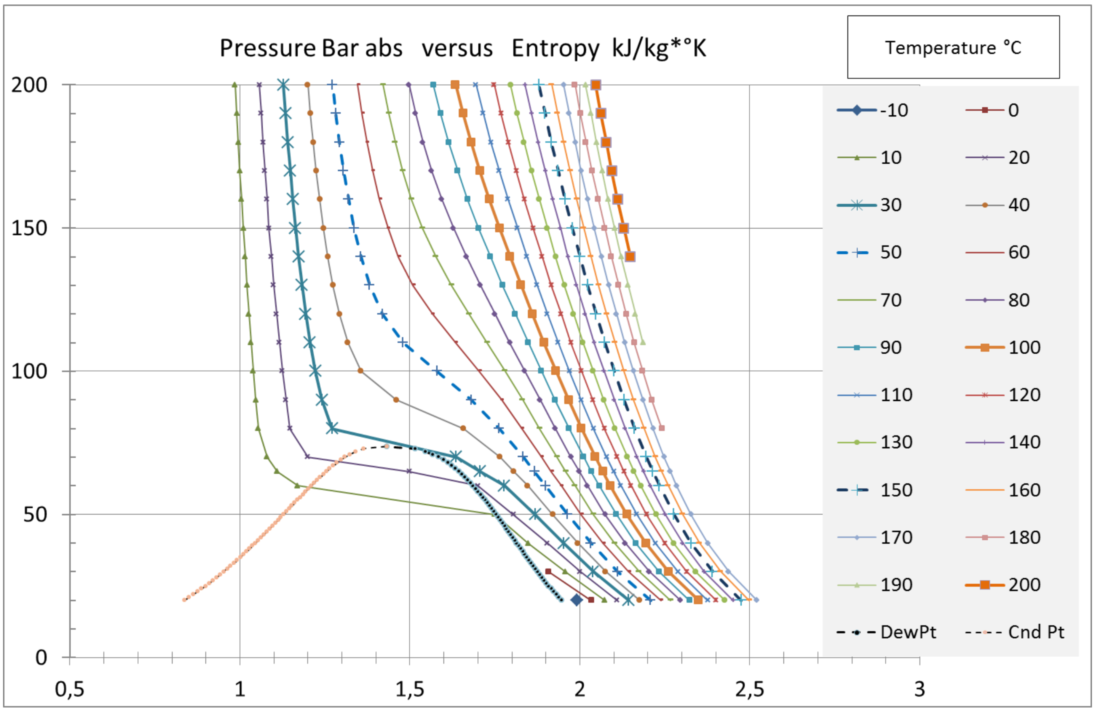



*Figure A6 – Pressure versus entropy (abscissa) and temperature lines with dew and condensation lines*