COMPARATIVE STUDY OF HEAT PRODUCTION BY COGENERATION OR HEAT PUMP

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Considering Carnot cycles, it is shown that reducing the power of a thermal power plant to produce cogeneration or using this difference in power to run heat pumps is equivalent in terms of overall performance. Practically, this is however not the same. This conclusion is put in evidence when considering an actual 280 MW power cycle and R134a, R600 and R717 heat pumps. It is shown that depending on the operating temperatures of the heat pumps and the heating network transmission losses, the overall cogeneration performance can be higher than the use of heat pumps in many configurations.

Keywords: rational use of energy, waste heat, power plants, heat pumps, cogeneration

1. Introduction

In France, over 37% of the primary energy is lost in energy processing and conversion, including a large part to generate electricity. In recent decades, an increasing share of that electricity has been used for meeting home heating needs by simple Joule effect, which consists in degrading a noble energy into heat, without intermediary benefit.

One way to improve power plants efficiency, which has been known and implemented for a long time, is the combination of heat and power production (CHP) or cogeneration. Some of the heat normally transferred to the environment by the plant can then be used for domestic heating through a district heating network. Another way of saving energy is to foster the final heat production thanks to heat pumps.

The aim of this work is to assess the relative significance of various forms of cogeneration and heating by heat pumps with a view to save energy. For this, a basic cycle of a real power plant is considered. In a cogeneration system, electrical power is reduced by a value equal to that which is converted into heat by Joule effect or heating by the heat pumps, some extraction flow rates being increased at the expense of those in some turbine stages. When heat pumps are used, two cold

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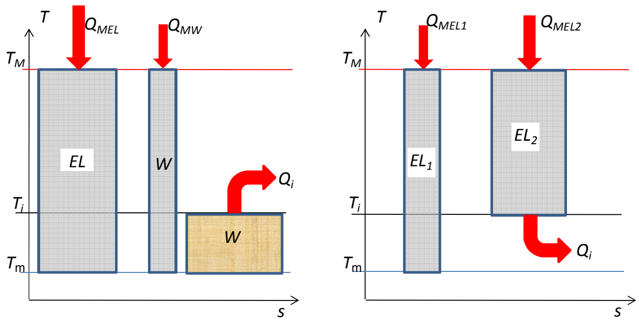
source temperature values are considered: 40 and 90 °C.

2. Analysis from Carnot cycles

The comparison between the cogeneration and heat pumps efficiencies can be made on a theoretical basis by considering Carnot cycles (Figure 1).



(a) (b)

Fig. 1. Production of electricity and heat: (a) heat pumps, (b) cogeneration

In case (a), a heat quantity Q_{MEL} brought at maximum temperature T_M can produce an electricity quantity EL, while heat Q_{MW} is used to produce work W used in a heat pump, producing heat Q_i at intermediate temperature T_i. In case (b), electricity is produced in part (EL_1) by a cycle receiving heat Q_{MEL1} operating between T_M and the ambient temperature T_m and in part (EL_2) by a cycle receiving heat Q_{MEL2} and operating between T_M and the intermediate temperature T_i, the thermal output Q_i of this cogeneration cycle being then used for heating.

In case (a), considering the two principles of thermodynamics, one can write:

$$EL = Q_{MEL}\left(1-\frac{T_m}{T_M}\right) \quad \text{and} \quad Q_i = Q_{MW}\frac{1-T_m/T_M}{1-T_m/T_i} \tag{1}$$

Noting $CE=EL/Q_i$, the set electric coefficient, the heat quantities used to provide a given quantity of electricity are:

$$Q_{MEL} = \frac{EL}{1-T_m/T_M} \quad \text{and} \quad Q_{MW} = \frac{EL}{CE}\frac{1-T_m/T_i}{1-T_m/T_M} \tag{2}$$

Summing up, we get:

$$Q_{tot} = \frac{EL}{1-T_m/T_M}\left(1+\frac{1-T_m/T_i}{CE}\right) \tag{3}$$

In case (b), the electricity production is the sum:

$$EL = EL_1 + EL_2 = Q_{MEL1}\left(1-T_m/T_M\right) + Q_{MEL2}\left(1-T_i/T_M\right) \tag{4}$$

while the heat produced is:

$$Q_i = Q_{MEL2} \, T_i / T_M \tag{5}$$

By introducing in equation (4) the expression of Q_i given by equation (5) and noting that $Q_{MEL1} = Q_{tot} - Q_{MEL2}$, we get an expression of the total heat exactly equal to expression (3), which proves the equivalence between the two solutions: heat pumps or cogeneration.

3. Characteristics of the reference thermal plant

The layout of the plant is given in Figure 2. It is a reheat Hirn cycle whose temperature and pressure are up to 567 °C and 167 bar, comprising 7 steam extractions (bleedings) and 8 reheaters (feedwater heatings) by heat exchange and mixing. The water characteristics and steam flows at various cycle points are given in Table 1. The entropy chart is shown in Figure 3.

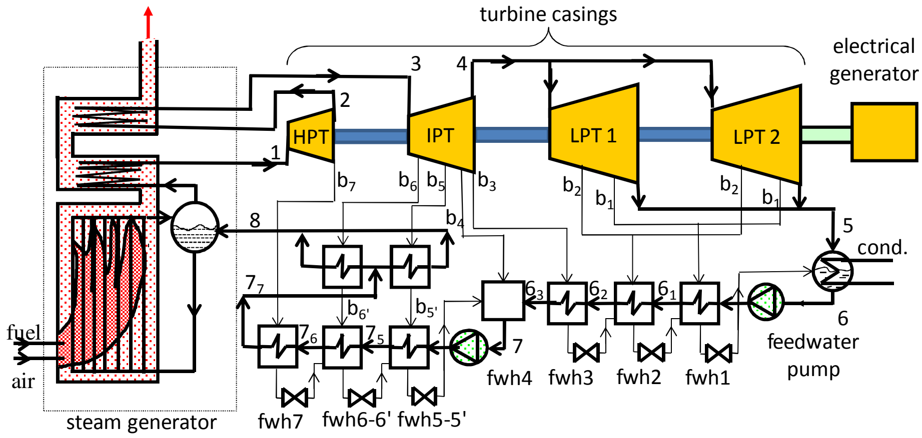


Fig. 2. Reference power plant layout

For such a cycle, neglecting the auxiliary consumption and pressure drops in the circuit and considering a 85% efficiency for all heat exchangers, calculations using the THERMOPTIM®[4] software give a power of 280 MW and an efficiency of 47.5%

Table 1

Characteristics of the reference steam cycle

Point	1	2	b7	3	b6	b5	b4	4	b3	b2	b1	5
Pressure (bar)	167	36.8	36.8	34.8	24.8	16	7.2	2.34	2.34	0.79	0.218	0.032
Temperature (°C)	567	348	348	566	513	449	342	213	213	116	62	25
T Liq-vap (°C)	351	246	245.5	242.2	223.5	201.35	166.1	125.3	125.3	93.2	61.85	25
Flow rate (kg/s)	204	192	12.1	192	8.1	10.35	10.97	153.4	9.17	8.72	7.92	136.8
Enthalpy (kJ/kg)	3475	3096	3096	3600	3492	3360	3147	2895	2895	2712	2530	2345

[4] This software was also used for all other calculations presented here

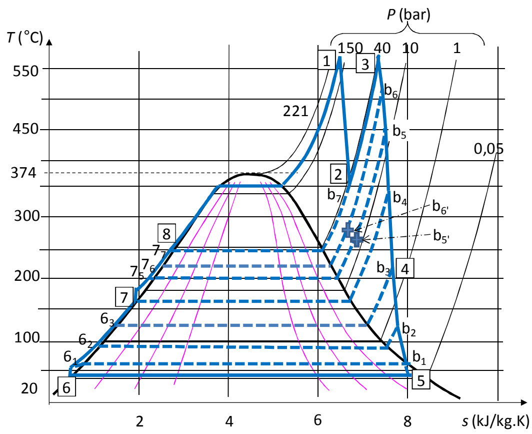


Fig. 3. Cycle characteristics in the entropy diagram

4. Comparative analysis of the various modes of heating

To compare the effectiveness of three heating methods (by Joule effect, heat pumps and cogeneration), it is *a priori* assumed that the electrical power used for heating corresponds to that produced by the low-pressure turbine, 40 MW, i.e. 14.2% of the plant initial power. This assumption allows, in a cogeneration mode, to minimize the impact on the turbine operation as only a turbine casing (LP) has to be disconnected.

4.1 Joule effect heating

Assuming 10% transmission losses in the power grid, the electrical power used for heating by Joule effect will be only 36 MW, for a 46.8% total effectiveness, defined as the ratio of the sum of thermal and electrical energy used divided by the primary energy consumption, representing a loss of nearly 1 percentage point as compared with the initial performance.

4.2. Heat pump heating

The heat pumps are classical vapor compression units with a compression isentropic efficiency of 90%. Three working fluids are considered: R134a, R600 (n butane), R717 (ammonia). In all three cases, the condenser sub-cooling is 3 K, the temperature differences between the sources fluids (thermal fluid SC and coolant SF) and the working fluid is 5 K (pinch). For R134a and ammonia, superheating is 3 K. Given the shape of its cycle, superheating is 12 K for butane.

Table 2 and Figure 4 show a marked improvement in the overall performance of the system (power plant + heat pumps). It also shows the strong influence of the heating source temperature and the best results are obtained with ammonia. However, for this fluid and a pressure of 55 bar, the maximum temperature exceeds 230 °C. As, in the case of butane, the pressure at the evaporator is below that of the ambient, the R134a should be used in this application.

Table 2

Performance of heat pump and overall production efficiency

Refrigerant	Temperature (°C)		Pressure (bar)		*COP*	Q_i (kW)	Global efficiency
	SF	SC	HP	LP			
R134a	8.7	31	10	3	6.4	230 841	0.797
		47	15	3	4.39	158 342	0.675
		59	20	3	3.42	123 355	0.616
		70	25	3	2.83	102 075	0.580
		78	30	3	2.39	86 205	0.553
		86	35	3	2.09	75 384	0.535
	3.7	31	10	2.5	5.53	199 461	0.744
		47	15	2.5	3.95	142 472	0.648
		59	20	2.5	3.16	113 978	0.600
		70	25	2.5	2.61	94 140	0.567
		78	30	2.5	2.23	80 434	0.543
		86	35	2.5	1.96	70 695	0.527
R600	8.4	29	3.5	0.8	5.7	205 592	0.755
		42	5	0.8	4.36	157 260	0.673
		61	8	0.8	3.17	114 338	0.601
		76	11	0.8	2.57	92 697	0.564
		88	14	0.8	2.18	78 630	0.540
R717	8	31	15	4.3	6.45	232 644	0.800
		50	25	4.3	4.32	155 817	0.671
		64	35	4.3	3.49	125 880	0.620
		76	45	4.3	3.02	108 928	0.592
		85	55	4.3	2.7	97 386	0.572

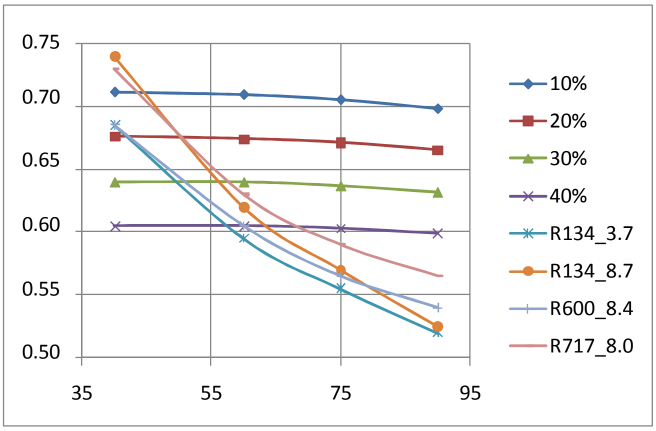


Fig. 4. Overall efficiency of power + thermal generation depending on the hot heat source temperature for cogeneration (with various values of the network losses) and heat pumps

4.3. Heating by cogeneration and heating network

Cogeneration is based on the extraction of steam at point b3 (exit of the IP turbine) whose initial flow rate (9.17 kg/s) is increased with that which feeds, in the reference cycle, turbine LPT2 (approximately 80 kg/s) which then provides no power (Figure 5). Temperatures at the use exit (point h2) move in the same range (40 to 90 °C) as those of the thermal fluid entering the heat pumps. The temperature difference of the heating network water through the recuperator exchanger is set at 20 K in all cases. The evolution of the overall performance is given in Figure 2 for losses ranging from 10 to 40% of extracted energy.

We note that, unlike the case of heat production by heat pumps, the overall efficiency does not change much with temperature and, of course, the losses have a strong influence on performance. Despite this, we note that with 40% losses, the overall efficiency, greater than 0.6, is not only well above the basic performance of the plant (47.5%), but also higher than the overall performance obtained with R134a heat pumps running with a cold source temperature of 9 °C and a heat source temperature above 60 °C.

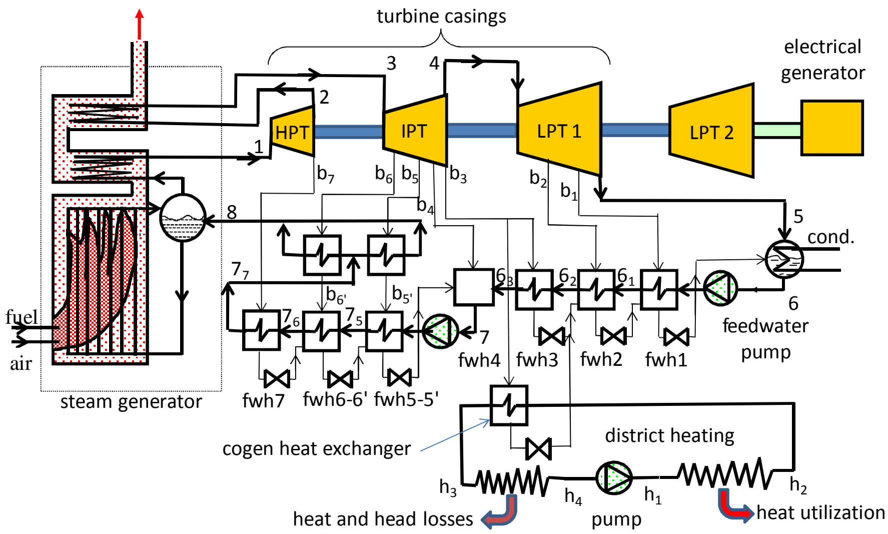


Fig. 5. Operating layout of the plant without second LP turbine and with cogeneration

A simple analysis of pressure drops (with a velocity of 2 m/s) and heat losses (with a fibrous insulation having a thickness equal to 20% of the pipe radius) shows that these losses for a 100 km back and forth network, remains in all cases less than 20% or 10% when the water network temperature is below 70 °C. Moreover, the pumping power needed to make up pressure drops, which is lower than the thermal power lost at high temperatures becomes higher at low temperatures. Thus, the pumping power compensates in part or totally the thermal losses. Taking into account this fact and considering the production efficiency of the electricity consumed by the pumps, it means that the overall network losses are broadly equal to 10% of the heat provided. Heat production by cogeneration becomes then greater than that of R134a heat pumps as soon as the hot source temperature exceeds 45 °C.

Due to the pressure at the outlet of the IP turbine and the corresponding saturation temperature (125.3 °C), the maximum temperatures that can be expected in h2 and h3 are approximately 100 and 120 °C. With 10 or 20% losses, the overall performance is respectively 0.694 and 0.661. For higher network temperatures, steam must be extracted at b5. The 40 MW decrease in electricity production is then distributed evenly between the IP and the two LP turbines as shown in Figure 6. The corresponding overall performance is shown in Figure 7 which was obtained assuming a 20% loss for points at 120 and 130 °C and a 25% loss for the three other points in order to take into account the increased network heat loss with temperature. Let us recall that, due to a thermal difference of 20 K in the secondary cogeneration exchanger, the maximum temperature reached with this configuration is 180 °C.

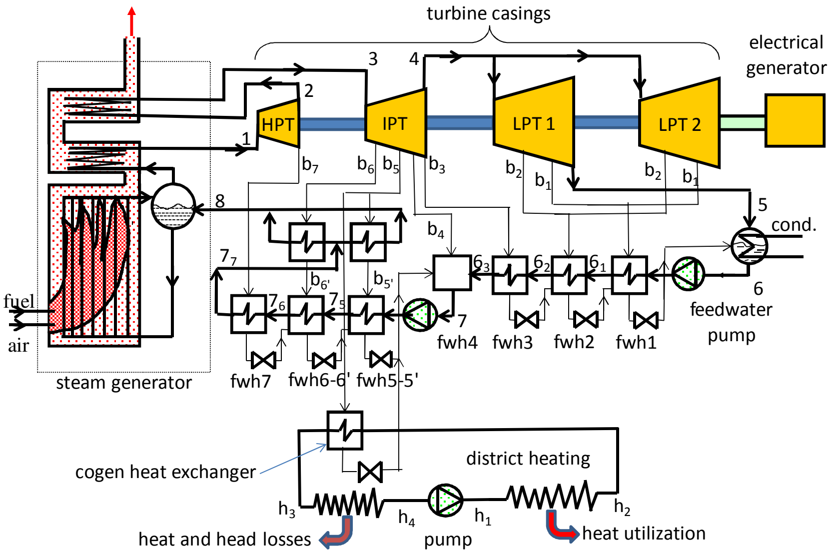


Fig. 6. Operating layout of the cogeneration power plant with b5 heat extraction

We note that the overall performance drops significantly when changing the extraction level, but this performance remaining however better than that obtained with heat pumps as soon as the hot source temperature exceeds 70 to 80 °C for a cold source at 9 °C.

5. 80 MW electric power decrease case

For the results presented above with a 20% loss, the cogeneration electricity coefficient *CE* is around 1.5. To highlight the influence of this factor, a study was done assuming that the full power of the LP turbine, 80 MW, is set to zero. In this case, the whole flow-rate in the LP turbines and extractions is used for cogeneration. The electricity coefficient is then about 0.6 with 10% network losses. For heat pumps, we consider a power consumption of 72 MW.

Figure 8 shows this influence. It highlights, on the one hand the superiority of cogeneration on the use of heat pumps as soon as heat is provided above 50 °C, the cold source being at 9 °C, on the other hand, except when the temperature is very low, cogeneration results are all the better as the power coefficient is low.

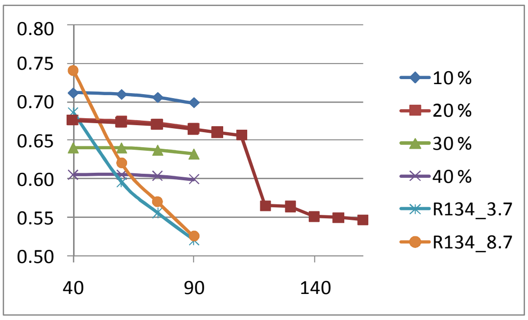


Fig. 7. Overall thermal + power generation efficiency depending on the heat temperature in cogeneration and heat pumps

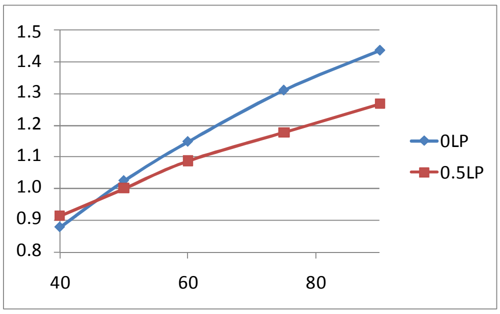


Fig. 8. Ratio of overall efficiencies CHP / heat pumps in the case of half LP production (0.5LP) and zero production (0LP)

6. Conclusion

Starting from an actual power plant and considering, on the one hand, that a fraction of the electricity is used to heat by Joule effect or by heat pumps, and on the other hand that this fraction is not produced for the benefit of direct thermal cogeneration, we have shown the superiority of heat pumps when used in mid-season (temperature of cold source ranging from 8 to 10 °C) to produce heat at low temperature (generally less than 50 °C). However, cogeneration, even if the network length is large (here 100 km) gives better results when the heat is provided above 50 °C. This advantage is further enhanced when the electricity coefficient CE decreases.