Cogeneration in District Heating Systems

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Abstract.

The District Heating systems (DH) are distribution systems of thermal energy, normally in the way of hot water that is supplied to great areas of population, so the users of these systems use them in the heating of their buildings and in the preparation of the hot tap water that is consumed in the buildings.

The kinds of power stations that supply the thermal energy to the DH systems are as wide and varied as could be imagined: big boilers rooms, geothermal stations, solar stations,…, but mainly and due to the high energetic efficiency, the power stations which have been widely spread in the last years are Combined Heat and Power plants (CHP).

In this article, it is presented a brief description of the DH systems in the first place and then, it is shown the main advantages that the centralized thermal production has, compared with the individual systems, and the kinds of CHP Plants more extensively used in the DH systems are described.

Furthermore, this article focus on the different aspects that contribute to optimize the electric and thermal production in the CHP plants, as the operation way, thermal storage or the requirements that the DH systems have to achieve.

Key words

Power Station, Thermal Energy, Electricity, Combined Heat and Power (CHP), District Heating (DH)

1. Introduction

District Heating (DH) is a technique which thermal energy is supplied by a pipe network generally by hot water and more rarely by steam, to great density of population, this energy is normally used for heating and to produce hot tap water to be consumed in buildings, and in special situations in industrial consume.

Obviously, the thermal needs in a DH network are very different as the time pass by; according to the season (in summer are lower than in winter, and this is due to the lack of heating demand), and according to the time (the heating needs are not constant during the day, as well as the hot tap water). In this kind of systems, it is estimated that the thermal demand is lower than the 75% of the peak demand during the 75% of the year; due to this fact, and to get the economical optimization of the installations, in the systems, peak power stations and base stations are built.

The peak stations, because of they work very short periods of time during the year, are associated to very low costs of installation and usually to high costs of energy, normally to gas boilers.

The base stations are associated to low costs energy systems and normally to high costs of investment, as are the geothermal stations and the solar stations; or to systems to get the maximum use of residual energy as the solid-waste incinerator or the farming and forest wastes or the using of residual industrial heat, but over all, the cogeneration systems are used.

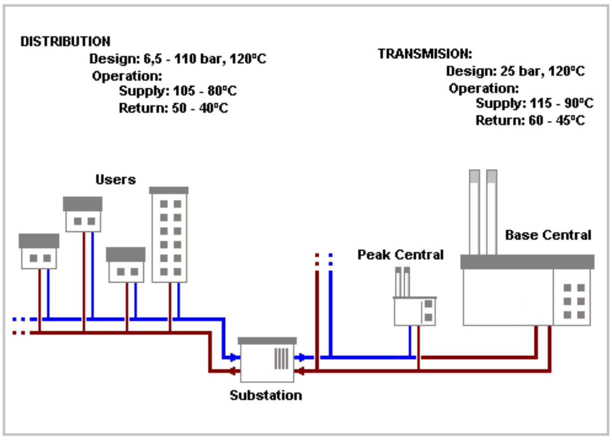

Fig. 1. Drawing of a simple DH system

The DH systems can be very simple, Fig. 1, very little and independent systems in which only one power station supplies all the heat of the whole system, in this case in the itself station, it is situated the base and the peak stations; or complicated, Fig. 2, which is the join of a number of simple systems by transmision pipes, in this case there are a great range of stations, operating, ones as base stations and the others as peak stations.

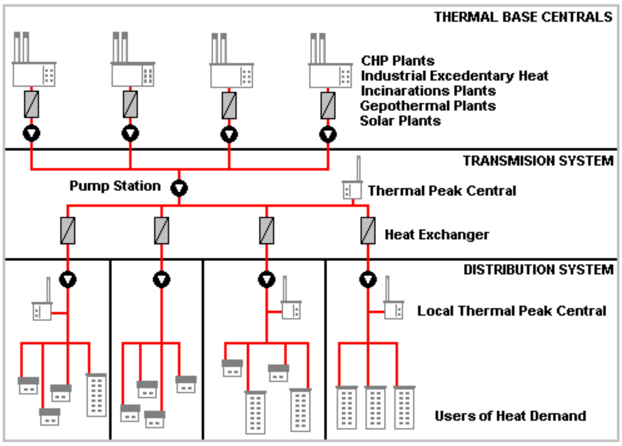

Fig. 2. Drawing of a complicated DH system

2. Advantages in the thermal production in power stations

The main advantages that there are in producing thermal energy in power stations with regard to produce this energy in an individual way, are at least the following:

- Great facility to change the fuel uses faced with varied situations, as can be a changing prices policy, because it is technically and economically easier to change the production in a power station than in numerous individual systems. This, allows to be more flexible to re-operate the consume of primary energy, which can allow to optimize in an economically way the system operation.

- The purchase price of the fuel is reduced because a power station is a qualified consumer, and the individual consumers are not.

- The performance of the thermal generation is always next to the optimum efficiency, because the fine tuning, maintenance and the correct operation of the power station are carried by specialized staff, while in the private residences there is a lack of this kind of service.

- The emissions of pollutants are reduced, because apart of the specialized staff who controls the correct operation of the installation, the filters planting, suitable burners and the rest of the elements is easily feasible in a power station, while is very difficult practice application in individual installations.

- The use of local energy resources as the geothermal energy, excess industrial heat, farming wastes, mainly the straw, and the common wastes are allowed because this technologies and fuels or energy sources are not available to the individual users.

- New stable jobs would be created.

- The noise in the private residence is reduced because it is produced in the power station, where, if it is necessary, can be treated in a suitable way.

- There are not fuel tanks in the private residences, fuel distributions networks in the cities, or traffic of fuel trucks in urban zones, which is something very important to the security of these places.

- And at last but not the least important, it is very easy to adapt a system to combine the mechanical and thermal energy (CHP, Combined Heat and Power), normally associated to a cogeneration.

3. Kinds of cogeneration stations in district heating systems

The heat sources used in the DH systems are as wide and diverse as can be imagined, they are the geothermal stations in Island, stations with solar collectors and the typical power stations of boilers, in which coil, fuel, wood, etc. can be burnt; even some power stations use heat pumps and these stations are used to rise the thermal level of any industrial waste heat.

But the kind of power station which has had the widest development and welcomed during the last years in the DH systems, has been the CHP, because the usable energy, which can be obtained in the stations with the fuel used is very higher than the one which can be obtained in a conventional power station of electric energy.

A conventional power station which drawing is shown in Fig. 3, although the usable energy values are particular for each station, it can be said that in a general way, they have a performance in the generation of electricity of about 45%, being the thermal losses in the water of condensation around 47%, and a 8% between the smoke and the structural losses.

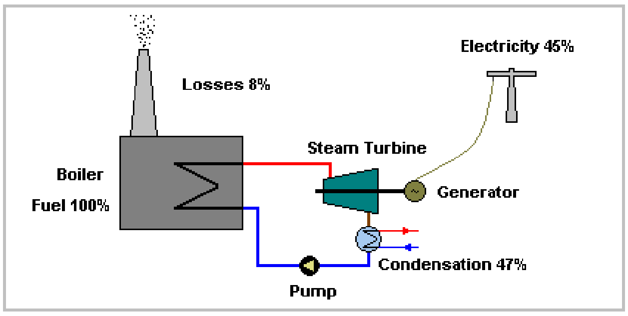

Fig. 3. Drawing of a thermal power station of electric generation

Among the systems used in the CHP in the production of DH, can be quoted the following:

- The "back-pressure" (BP) stations, Fig. 4, in which it is produced around the 36% of the electricity, while they used the 56% of the energy that the fuel gives in the production of the hot water for the DH system, which makes that the total performance of the station is around the 92%, approximately the double than in the conventional power station.

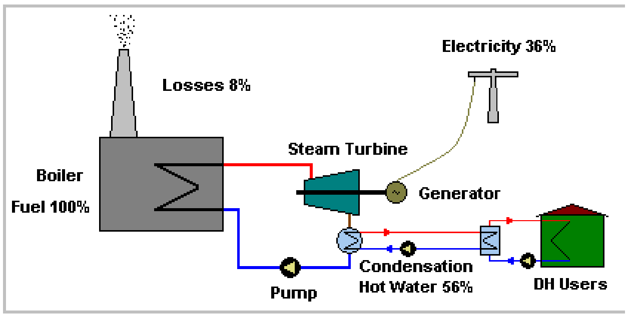

Fig. 4. Drawing of a "back-pressure" station

The production of electric energy ratio (E.P.R.) over the heat in this kind of stations is around the 64%.

$$\text{E.P.R.}_{\text{BP Station}} = \frac{\text{Electricity}}{\text{Heat}} = \frac{36}{56} x\, 100 = 64\% \qquad (1)$$

The operation of the stations is based on the Carnot Cycle, Fig. 5, which theoretical performance is as follows:

$$\eta_{\text{Carnot}} = \frac{T_{\text{supplied}} - T_{\text{condensation}}}{T_{\text{supplied}}} = \frac{T_1 - T_2}{T_1} \quad \text{T (K)} \qquad (2)$$

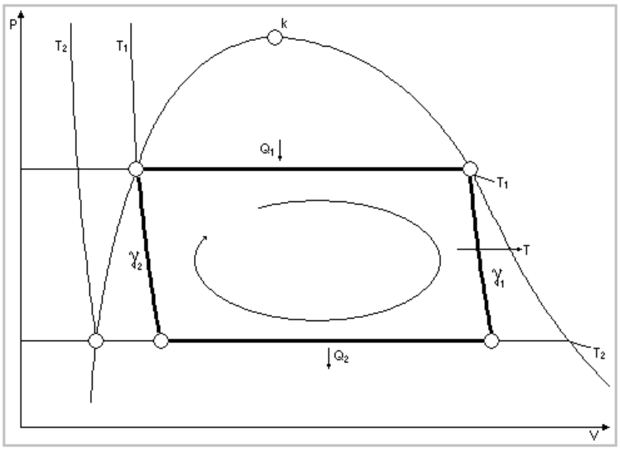

Fig. 5.Carnot Cycle

Graphics in which the efficiency of the Carnot Cycle versus the condensation temperature, for different supplied temperatures it drawn in Fig. 6.

The analysis of the Fig 6, shows that the performance goes down when the supplied temperature goes down too, being this effect more appreciable with very low supplied temperatures; and as the performance decreases when the condensation temperature increases its value.

This last effect is which produces that the electrical production in a BP station is lower than the one obtained in a conventional station; and in the conventional station the condensation it is done with river or sea water temperature, normally to temperatures next to 40ºC, while in a station used to heat water for DH uses, the condensation takes place between temperatures of 85ºC and 120ºC, because the water of DH, has to achieve the necessary temperature to be use in the DH network.

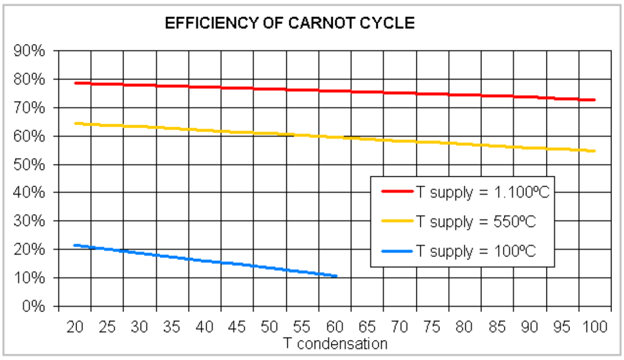

Fig. 6. Carnot Cycle performance versus condensation temperature for three supplied temperatures

The increase in the condensation temperature produces a decrease in the useful energy which is obtained in the steam turbine, and in the electricity produced in the station, and this is higher as higher is the condensation temperature rise, so to maximize the electrical energy produced in the station, it is very important to decrease to the minimum the condensation temperature; this effect is obtained when the supplied temperature to the DH is minimized or when the users can reduce the return water temperature.

If it is desired to replace a conventional station by a BP station in which it is used 100 units of fuel to produce 45 units of electricity, and it is desired to hold the electricity produced, the primary energy consume (P.E.C.), should be higher, it should be around 125 units.

$$\text{P.E.C.} = \frac{45}{36} x\ 100 = 125\% \qquad (3)$$

So, in this way the heat production in the station would raise to 70 units.

$$\text{Produced heat} = 125\ x\ 56 = 70\% \qquad (4)$$

And all of this means that in this kind of stations, producing the same quantity of electricity than in the traditional power stations, it is consumed a 25% more of fuel, and to this increment can be obtained 70 units of heat, so if the price of the electricity produced is considered constant, the performance of heat generation in the station is about 280%.

$$\text{Heat Performance} = \frac{70}{25} x\ 100 = 280\% \qquad (5)$$

- A CHP station of extraction of electrical energy, combines the operation of the two systems described above, the conventional and the BP stations, Fig. 7, and this system is able to use water to the refrigeration of the condenser so it operates as a conventional power station, and this is done when there is no thermal demand, or it is covered by other stations, obtaining a 45% of the electricity over the fuel used; or produce hot water to be supplied to the DH network with an electrical production of the 36%.

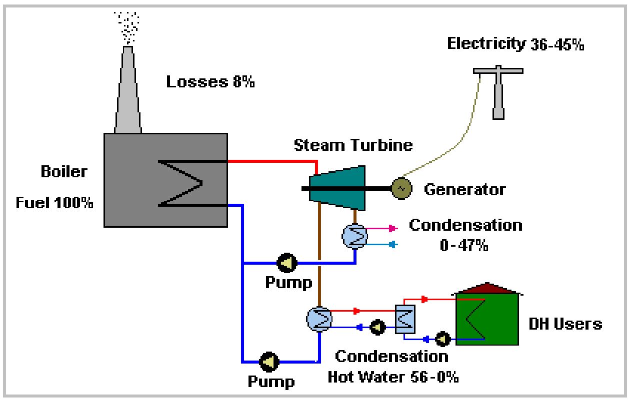

Fig. 7. Drawing of an extraction station

These stations have the characteristics that its electricity production ratio over the heat is variable, because it can fluctuate between no producing useful heat as an electrical power station and the 64% when it operates as a BP station.

The water of the DH is produced between 100 and 120ºC, and the annual performance of this kind of stations is between the 70% and the 75%, which is between a 25 and 30% higher than in a conventional power station.

- Combined Cycle stations, Fig. 8, in this kind of stations it is used a gas turbine joined to an electric generator, and the exhaust gases go throw a recuperation boiler in which steam is produced. This steam is used to feed a steam turbine, joined to a second electric generator, and it is when the steam condensates when the heating of the water used in the DH is produced. This water can be heated in its final period in a recuperation boiler.

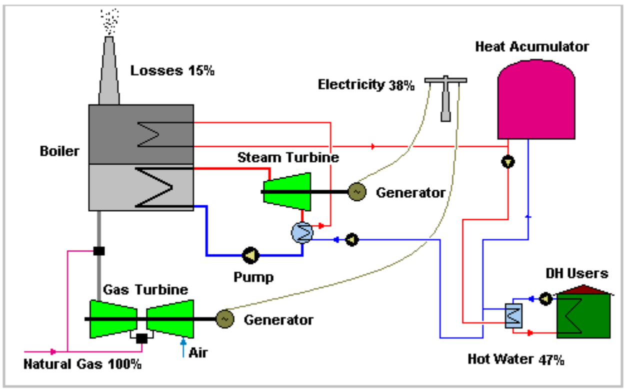

Fig. 8. Drawing of a combined cycle station

These stations produced around the 38% of the electricity, around 47% of heating and there is a 15% of losses, so the electrical energy production ratio in these stations is around the 80%.

$$\text{E.P.R.}_{\text{ Combined Cycle}} = \frac{38}{47} x\, 100 = 80\% \qquad (6)$$

- There are smaller stations, such the ones that use diesel combustion motors, Fig. 9, it is normally that these motors have associated a turbo; in these stations, it is used water coming from the refrigeration of the motors as well as the oil refrigeration to pre-heat the water, which finally is heated with the exhaust gases that are evacuated by the motors; there can be heat recuperation that cools the air that goes out of the turbo and that prepares totally a little portion of the water used in the DH.

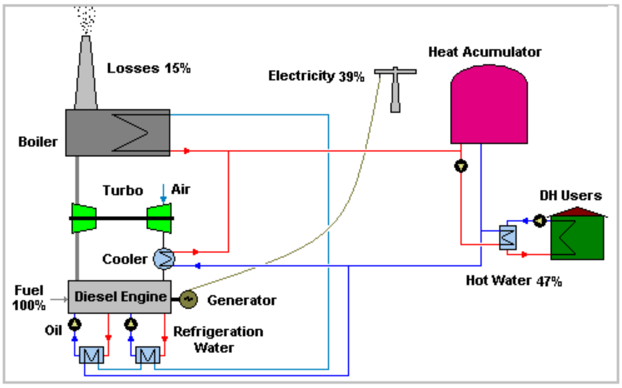

Fig. 9. Drawing of a station with a diesel combustion motor

In these stations it is produced a 39% of the electricity, and a 46% of heat with a 15% of losses, so the electrical production ratio over the heat is around the 84%.

$$\text{E.P.R.}_{\text{Diesel Motor}} = \frac{39}{46} x\, 100 = 84\% \qquad (7)$$

- There are also stations with gas turbines, Fig. 10, and in them, it is used the exhaust gases to heat the water of the DH, and these stations produced around the 30% of the electricity and the 55% of the heat, so the electrical production ratio is around the 54%.

$$\text{E.P.R.}_{\text{Steam Turbine}} = \frac{30}{55} x\, 100 = 54\% \qquad (8)$$

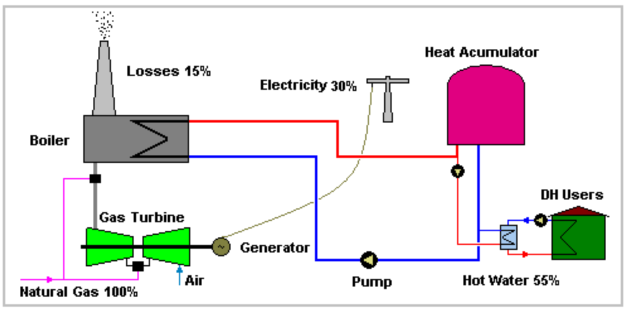

Fig. 10. Drawing of a station with a gas turbine

Although the relation between the thermal and electrical production of the different stations is not fixed for each kind of station, because it is particular for each of them, in Table I it is shown an example of the electrical and thermal production for the different kinds of stations of CHP used in the DH systems. The data are indicated over a hundred per cent of the used fuel.

Table I.- Resume chart of the production (%) in the different kinds of CHP stations

	Power Station	BP station	Extraction station	Combined cycle	Diesel Motor	Gas Turbine
Termal Production	0	56	0 - 56	47	39	30
Electrical Production	45	36	45 – 36	38	46	55
Losses	55	8	8	15	15	15
Performance	45	92	45 - 92	85	85	85

From the analysis of the Table I, it can be observed that the global performance of the CHP stations is much more higher than the one which can be obtained in the electrical production stations.

4. Operation of power stations in DH systems

The way of operation of the DH power stations depends if them are base stations or peak stations.

The operation of the base stations is about of producing the highest quantity of possible electricity in the peak electrical hours, so the highest and possible economical performance could be obtained.

The peak stations have low starting costs, although it has to be taken in consideration that to start a station has a cost, which is higher as more time has been stopped, because it has suffered a higher cool; but the operation costs of these stations are higher than the ones of the base stations, because they do not produce electricity.

Fig. 11. Hot water storage tank in a DH station

The highest economical profitability of the DH systems in comparison with the operation of the stations is obtained when the necessity of the peak stations is lower, and higher is the electrical energy produced in the electrical peak hours, and to do this, these stations have big tanks to accumulate hot water, Fig 11, which correct operation helps to hold the DH service maximizing the price of the electrical energy produced.

In the Figures 8, 9, and 10 it is included the representation of an accumulation tank, tank which could be represented in a similar way in the Figures 3, 4 and 7.

The aim of the station is to produce the maximum of electricity in the periods in which this electricity is expensive without reducing the thermal supplied, so to decide the way of operation of the station, apart of knowing the thermal demand, it is necessary to know at least the following parameters:

- The hourly thermal demand.
- The maximum and minimum capacities of operation of the station (thermal and electrical).
- The capacity of the storage tank.
- The heat accumulated in the tank.
- Hour of the day and price of the electricity.
- Delay time in the thermal supplied to the network.

It has to be taken in account that the decisions reached in a determined moment about the loading and unloading of the accumulation tank affect to the future operation of the station that is because its operation is very important.

The electrical production versus the thermal production in an extraction plant could be represented in a diagram like the one in Fig. 12, knowing the parameters enumerated above. It can be obtained a great economical performance if the station is operated in a correct way.

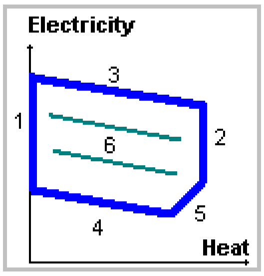

Fig. 12- Possibility and operation limits in an extraction station

The operating limits of an extraction plant are the following:

1. Condensation with water to produce only electricity.
2. Production of the maximum heat.
3. Production at maximum load, if the heat increases, the electrical production decreases.
4. Operation at minimum load of the boiler.
5. Operation like a backpressure station.
6. Operation at constant fuel consumption.

As an example, in Table II it is show a standard price of the electricity.

Table II.- Standard price of the electricity.

Hour	0-6	6-12	12-18	18-0
Price	50	100	150	50

The ideal operation of an extraction CHP station, taking into account that the thermal demand has to be covered and that it has not to be excessive heat, it has to be to produce at full load in peak hours, and the rest of it in the BP range, in off-peak hours at minimum load, and in normal hours at maximum load, as is shown in Fig. 13.

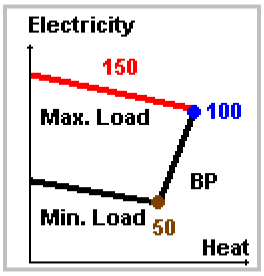

Fig. 13. Optimum operation in an extraction station

If the DH system has two stations, a BP station and an extraction station, the ideal operation is got in the off-peak hours with the BP station operating at the maximum range and the extraction station at minimum load, Fig. 14, while in the peak hours, Fig. 15, the extraction station has to operate at the maximum; although the BP station has to be taken in account due to its high costs in the starting moment, so this station should never stop.

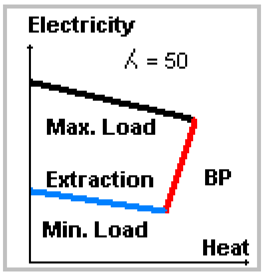

Fig. 14. Operation in off-peak hours with two stations

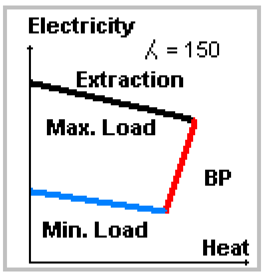

Fig. 15. Operation in peak hours with two stations

If there are two units that produce the same, the control strategy that is more efficient is to cover the lower demand with one unit, to the 60% of it, and if there is more demand this one is covered with another unit till the 100% of the second unit, and if the demand is higher than this one, it is covered with the remaining 40% of the first unit.

Although this means to start and stop the station in a constantly way, it is better to cover the demand with both units at the same range. The worst results are obtained when it is operated with the units in a serial way, first with one of them and then if it is totaly completed (100%, with the other one).

5. Requirements of the system for the correct operation of the power stations

The rates for the users of the DH systems have several items: ones which are fixed and based in the square meters of the housing and the heating area, and another variable item, which is about the energy consumed (product of the volume of DH water consumed and the thermal difference in the DH water).

But to increase the electrical production of the power station, as well as to decrease the thermal losses in the pipes, it is necessary that the condensation and the supply temperature should be done at the lower temperature.

Moreover, to reduce the energy consumption in the pumping, it is necessary to minimize the amount of water pumped, so the thermal difference that the users of the DH network should produce in the water must be as highest as possible.

If the water flow is minimize, the size of the pipes could be reduced, which is cheaper and has lower thermal losses because the dissipation area is smaller.

So, to get low temperatures in the network and to increase the system efficiency, the variable item of the rate has corrector factors which penalize the consumers who produce a low thermal difference in the DH water, while the consumers who produce a big thermal difference are improved.

Referring to the thermal demand of the system, it is very different during the year and during the day, for example, in the blocks of flats there is a great peak of consumption in the mornings due to the hot tap water demand, an another peak in the afternoons; and the office buildings or the institutional buildings the demand decrease at night because the building heating control usually decrease indoor air temperatures during the night.

To get a decrease of the peak levels, the electricity companies follow a wide range of strategies, among it can be remarked the following:

- To decrease the peaks, Fig. 16, for example the installations controls do not provide heating when they have a strong demand of hot tap water, something similar that happens with the domestic heating and hot tap water boilers.

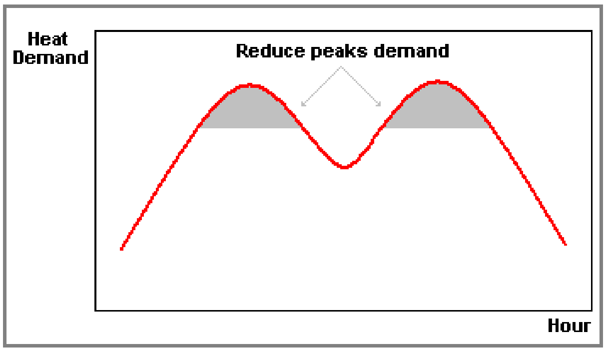

Fig. 16. Reduce the consumption peaks

- To change the consumption habits moving the thermal load at hours that it is low, Fig. 17.

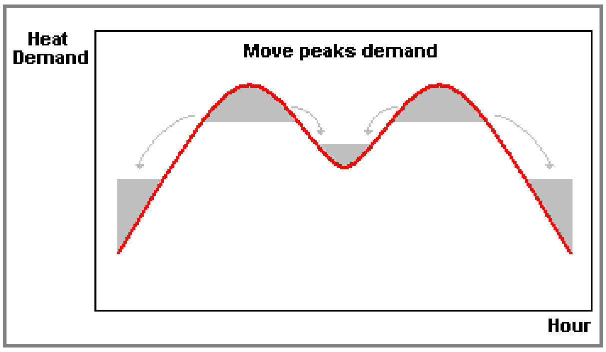

Fig. 17. Move the consumption of the peaks

- To reduce the consumptions, with the best insulation in the private residences, or installing heat recovery systems in the air extracting systems, Fig. 18.

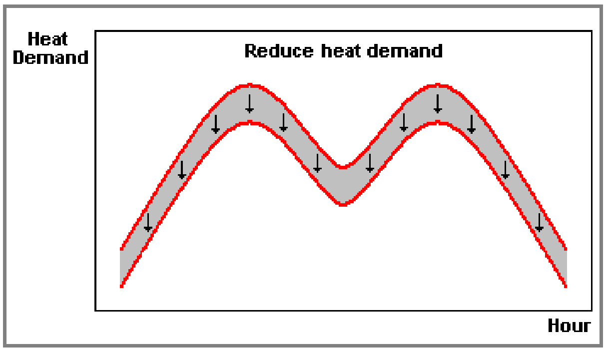

Fig. 18. Reduce the consumption

- To increase the consumption in the low demand moments, encouraging this with special fares, Fig. 19.

The DH systems based in geothermal stations and due to the free heat source, and not to the operation way, have the peculiarity of not having a returning pipe; when the users has obtained the heat of the water, they put it on the city exhaust water pipes. The peculiarity of these stations is that the companies do not charge for the heat supplied, but they charge only for the volume, because as there is not return, the companies do not mind about the thermal difference that the users produce in their installations, but the volume that has to be pumped by the pipes.

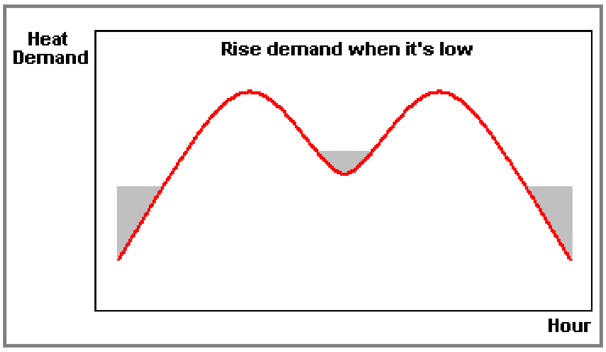

Fig. 19. Increase the consumption in the low demand periods

The systems based on the solid waste incinerators have a constant supplied and fixed fuel supplied, and the problem that is not feasible to carry out fuel storage, because the stations are near the user's buildings.

When this kind of stations operates connected to a great DH distribution system, there is not any problem, but when they operate in small and isolated systems, there is the problem in summer, when there is not heating demand, they have to burn more fuel than it is necessary for the DH demand; in these situations, this kind of companies are encouraging among their customers, with low prices in summer, the installation of absorption refrigeration systems.

So the reason why the DH systems were able to supply the thermal demand of the users in an efficient and the more economical and possible way, it is necessary that the installations of the users were correctly design, basically:

- The heating installations must work at low temperature, as the radiant floor systems; or in the case of using the typical radiators, these must be bigger than usually they are.

- The heat exchangers in which the hot tap water is produced must be bigger, because the temperature of the primary is lower.

6. District Heating and Cooling

District Cooling (DC) is a technique which is starting to be generalized in the urban centers of countries like USA, Sweden or Korea; with this technique chilled water is distributed, normally between 5 and 12ºC, from a big chiller plant to a great wide amount of places, normally urban places. The use of DC water is for the cooling or refrigeration of the buildings, essentially of commercials, hotels and offices use by air conditioning.

In relation to the chilled water production, the DC systems can be classifying under three big groups:

• Autonomous systems, in this case they usually have chillers with centrifugal compressors, because these ones can be adapted perfectly to this use, in which a great production at high temperature is required.

• Singular systems, like the one that there is in Toronto, in which water from the Ontario lake is flown; the water is obtained from 80 m of depth, where the temperature is around 4 or 5 ºC all the year.

• Systems associated to the DH, in which the cold production is made with absorption machines. This is what is known as District Heating and Cooling (DHC), Fig. 20. DHC is about using the hot water supply of a DH system to feed the generator of the absorption machine or machines, normally of BrLi-H_2O, in which the water that the DC system supplies, is chilled.

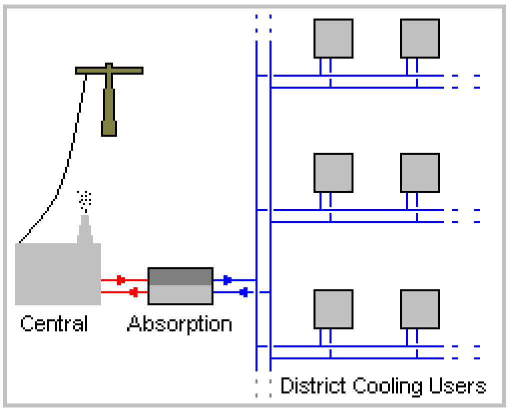

Fig 20.- Drawing of a DHC System

This last systems, the DHC, have for the DH thermal stations, at least the following advantages:

– The yearly hours of use of the thermal stations increases. In summer, the use of the DH systems is reduced, they are only use to provide and cover the demand of hot tap water, but if DC is produced with hot water, the using hours of the station increase and therefore its depreciation improve.

– In the simple DH systems which stations are incinerators, residual industrial heat, geothermal stations, and so on, which energetic source is constant and not storable, it is allowed their use in some periods that in no other way could be done.

– It is allowed the use of the thermal storage in water tanks, and it is possible to do it with hot or cold water; in the first case, the same storage can be used in winter and in summer.

7. Resume

In this paper the District Heating systems have been shown and described; The principle advantages of making the thermal production in big stations and not in an individual way have been enumerated; the fundamental parameters of the different kinds of thermal energy more use have been described: The cogeneration stations; the operation instructions and the guidelines of operation that the systems should have to optimize their operation have been shown; and finally the advantages that there are for the thermal stations if a DH system is associated to a DC system, have been submitted.

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