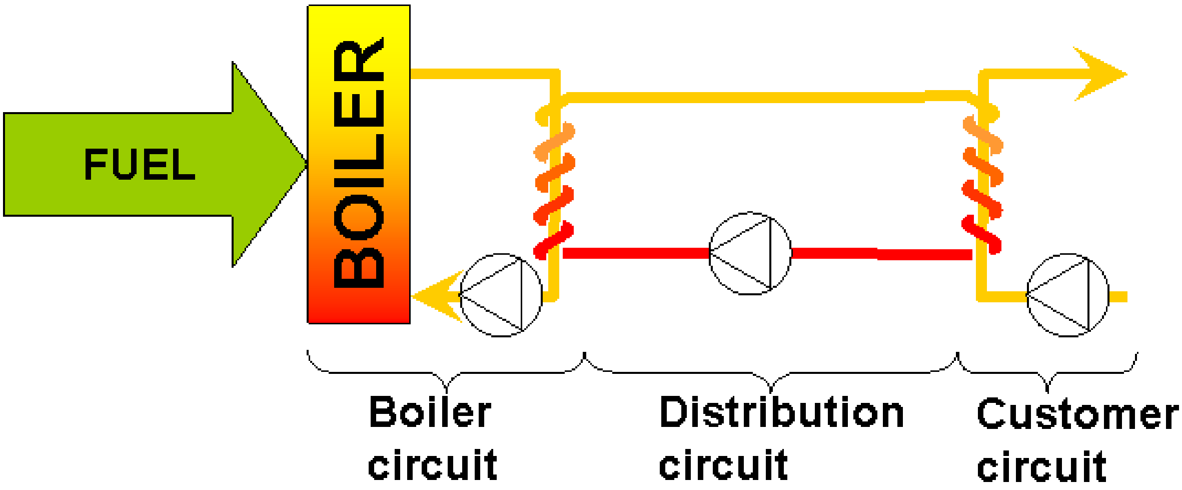
03-00: Introduction to small-scale district heating…

As a “small” district heating network, one would consider anything with a peak thermal power less than about 5-10 MW, but there is no strict limit.

The fundamental idea with district heating is simple enough, as shown by the schematic below:



Thus, the system consists basically of three serial circuits, a boiler circuit, a distribution circuit and a customer circuit. In practice, there will be two customer circuits – one for the tap water and one for the comfort heating system water. These will be manifest as two separate coils in the customer heat exchanger but for simplicity only one is included in the schematic.

The main components and their roles

<u>The boiler-end heat exchanger</u>

Looking at the schematic above it is obvious that the district heating system contains two heat exchangers – one at the boiler end and one with the customer. From a purely theoretical point of view, it might seem wise to exclude the boiler-end heat exchanger and to use the boiler circuit water also for the distribution, but this is not recommended for two reasons:

1) The part in the system most exposed to and most vulnerable to leakages is the distribution network, which may well extent for several kilometres across the township. In case of a major leakage – and if the boiler water is also the circulating water – the boiler will be dry and may suffer severe damage. Hence, the heat exchanger protects the boiler.
2) For maximum efficiency in the system as a whole it is important that the return water in the distribution system is as cold as possible – preferably below 50 ºC. Also the forward water should have the lowest possible temperature, and during summer this may be as low as about 65 – 70 ºC. Bringing water of such low temperature into (indirect) contact with the flue gases in a heat exchanger may induce condensation of water in the flue gases with subsequent corrosion in the heat exchanger. Hence the heat exchanger adds to the versatility and the robustness of the system.

The main circulation pump

One critical component in the system is the distribution pump, the pump distributing the hot water to the customers in the system. For robustness, there should always be installed a spare pump.

Pumping water around a distribution system requires a lot of energy and the power consumption in the main circulation pump is a matter worth consideration during the installation phase and when the total economy of the system shall be judged.

The power consumption in the main pump will – roughly – be proportional to the square of the velocity of the water in the pipes. Hence, doubling the velocity of the water will approximately quadruple the power consumption. On the other hand: If the velocity in the pipes is doubled, then the residence time of the water in the tubes is halved and hence the temperature drop is reduced.

Several decades of experience shows that a reasonable compromise between pumping power and heat losses is reached at water velocities (average for the whole system) about 1 – 5 m/s. The capacity of the main circulation pump and the diameters of the distribution pipes are thus chosen so that the water velocity ends up in this interval and the thermal power output is primarily adjusted by aid of the forward temperature and not by adjusting the flow.

The piping

The long-term economy and reliability of a district heating system is mainly determined by two parameters, namely the system efficiency and the life-time. Both these are to a great extent determined by the quality of the piping.

It is obvious that if the water velocity is set, then a small district heating system will mainly consist of pipes with a small diameter and the ratio of pipe surface area to water flow will be large. Hence will the heat losses through the pipe walls also become relatively large.

While large-scale district heating systems may exhibit pipe losses in the range of 5 % or even less in some cases, will the small-scale networks inherently have higher losses, up to 15, maybe even 30 %, in some installations. This cannot be avoided but the reason that district heating is still advantageous in small scale is because it provides means for fuel flexibility and for efficient flue-gas cleaning due to its scale. When a district heating system is installed in a domestic area, it will replace maybe 100 or more individual-home boilers which are typically not fuel flexible but dependant on one single – maybe fossil – fuel and which will have no flue gas cleaning at all. Replacing these with a modern, biofuel-fired boiler with flue-gas cleaning is in most cases an environmental improvement – even if the system efficiency may be as low as 70-80 %, energy wise. Replacing the individual boilers with compact heat exchangers, which are clean and silent devices and also removing the burden of chimney-sweeping from the individual households are side effects that are – according to questionnaires from Sweden – are also appreciated by the customers. To this comes the reduction of the risk for fires in the individual houses.

Nevertheless; the losses in the system may be significant and it is important that the pipes first installed are of the highest attainable quality with respect to their thermal insulation. It is also advantageous to use double tubing where the forward water pipe and the return water pipe are both enclosed by a common insulation with only one outer mantle.

The second demand put onto the distribution pipes – on top of the demand for thermal insulation – is the demand that they are diffusion sealed. One major reason for failures in district heating networks is corrosion, and corrosion is mainly caused by diffusion of oxygen into the distribution water. There are two ways to prevent the presence of oxygen gas dissolved in the water: Seal the tube walls so that oxygen cannot enter and – second – bind the oxygen if it enters. Both measures should be taken because corrosion may completely destroy the system quite rapidly.

In order to avoid in-diffusion of oxygen into the system, metallic distribution tubes should be chosen in the first instance. Even the highest quality plastic materials are still today (2011) inferior with respect to gas diffusion and since the network will contain metallic components – heat exchangers, valves, pumps etc – corrosion will be a problem once oxygen gas enters the distribution water circuit. New materials are continuously being developed and most probably will the heavy metal tubes successively be outflanked by light polymers, but so far are the metal tubes (often copper) the superior.

The second measure to abate the internal corrosion problem is to bind any oxygen entering into the system. So far this has often been done using *hydrazine* (N_2H_4) but since the hydrazine is in itself weakly toxic and may cause allergenic reactions, the use of this substance is debatable. It should also be mentioned that there are indications that hydrazine may be carcinogenic. Hydrazine is still used in Swedish district heating networks – though of course in very low concentrations – but is has been forbidden is some of the European states.

The customer heat exchanger

The temperatures and the flow rates through the customer heat exchanger will determine the temperature of the water with the customer. For the tap water circuit, the temperature at the customer side may not fall below about 55 ºC to avoid the establishment of *legionella* bacteria. For the comfort heating water, though, the temperature level is determined by the need and by the heating system actually used by the customer. With a water-borne floor heating system the temperatures needed are only about 30 ºC while an old radiator system may require temperatures up to 70 or even 80 ºC to provide a comfortable indoor climate.

The customer heat exchangers must thus be adjustable within fairly wide limits with respect to the customer side water temperature at the same time as they should be cheap. Care must therefore be taken during the procurement phase for the heat exchangers so that all these demands are met.

Finally, there is also the possibility to install absorption heat pumps at the customer end. This will provide for the possibility to use the district heating network to supply the customers with cooling. You will find the principle outlined in chapter 04-00.

System constants…

With a water-borne system spread out over a whole township or community, it is obvious that the system will not be fast.

District heating systems are generally dimensioned so, that the mean traversing speed of the water in the distribution network is in the interval 1-5 m/s. The reason for this is a compromise between the losses in the tubing – becoming larger as the water residence time increases – and the pump power, increasing in proportion to the square of the water velocity.

Hence, doubling the travelling speed of the water may reduce the temperature drop but will four-fold the pumping power. A reasonable compromise is typically found at about 3 ± 2 m/s.

For cases when the fuel supply system completely fails – cases so unlikely that they would normally not even considered – there might be a need for an accumulator tank to be installed in the system. Using the Swedish experience as a reference, the accumulator tank volume should best be approximately 0.5 m^3 per individual connected to the grid, so that if there are 300 households, altogether representing 1000 individuals, the accumulator tank for the district heating network should be about 500 m^3 in volume. Smaller tanks will of course improve the system performance too, but they will not be optimal, while larger tanks will be too big and may contribute to lower the total efficiency of the system.

In the upper end of the interval, and here the focus is on systems up to a few MW thermal power, where moving-grate boilers would be the most common, may also the combustion time constant be of relevance. Inside a reasonably sized moving-grate boiler there will at any instant be a few tonnes of burning fuel. In case of a sudden change in heat demand – an unexpected blizzard or maybe a stunningly still and sunny day suddenly intercepting a previously cold and windy period – will all this fuel represent a very significant time delay, especially if the demand is to turn down the thermal power. The distribution circuit as such will have the capacity to absorb a certain amount of surplus energy but then the mean temperature in the tubing increases and so do the losses. Again, an accumulator tank may prove useful in this case just as it will at sudden increases in demand.

The control system

District heating systems consist of three distinct water-based systems interconnected:

- The boiler circuit. This is the part of the system where heat is input from the combustion of fuel in the boiler and primary water – boiler water – is heated to a high temperature. In the case of combined heat-and-power production (see chapter 04-00 for more detail) the primary circuit may even contain steam. The boiler itself will – in the size range for these applications – operate under a modular control with a turn-down ratio about 1:3 or 1:4. To avoid corrosion and thus guarantee a long life-time for the boiler and the flue-gas system, the boiler water temperature should not be allowed to go to too low temperatures.

The heat from the boiler circuit is then transferred, via a heat exchanger, to

- The distribution circuit. This is the part of the system where heat is transported from the boiler to the customers. This is also the part of the system where the water velocity is typically set to about 1-5 m/s. Since, hence, the water velocity is more-or-less fixed, the main instrument to change the thermal power distributed is by changing the outgoing water temperature. In Sweden – where this technology has been used extensively since the 1940's – two types of networks are identified – namely "hot-water-systems" where the forward water temperature may exceed 110 °C, and "warm-water-systems" where the forward temperature is below 110 °C. During summer, the forward temperature may be as low as about 65 °C.

Finally, there is

- The customer circuit. The temperature with the customer tap-water may never fall below the temperature limit for growth of *legionella* bacteria – and this sets an absolute, low, temperature limit for the system as a whole.

Hence the control system will have to fulfil the temperature criteria in the customer circuit by actually controlling the temperature in the boiler circuit.

Omitting the heat exchanger between boiler- and distribution circuits may result in too low temperatures in the boiler convection pass and subsequent corrosion. The same thing applies in cases when the boiler set temperature is too low. Hence, the temperature set points in the different circuits are important to the total life of the components and the adjustment of the system thus becomes of utmost importance.

For office buildings, commercial buildings and other applications that are closed during night, the control system may also include a timer control so that the temperature set points are different between night and day, providing a lower night temperature. The theoretical basis for such a control is outlined in chapter 01-00, but the general conclusion is that the actual effect of a low temperature set point overnight depends strongly on the total thermal inertia of the building. The larger the thermal inertia – the lower the effect. Hence will this be an alternative in light, wood structure and wood frame, buildings, while heavy stone buildings will show no or only marginal energy savings by this method. The effect of low night temperature set points on energy saving is enhanced by the use of air-borne heating systems.

Economy of scale and time

The initial investment in a district heating system will always be significant and if nothing else is known one may assume that the investment in the distribution network is about the same order of magnitude as that for the boiler installation. And the cost for the boiler installation as a whole will be split in four parts of similar magnitude, namely the boiler itself, the boiler house, the fuel storage/handling/feeding system and the control system. To this comes the cost for the customer heat exchangers, but that cost would typically be paid by the customers themselves once they connect to the system.

To maintain a reasonably low total cost for the system it then becomes important to maintain a low variable cost in the system and to dimension it for a long lifetime. Again, the quality of the tubing – its thermal insulation and its ability to seal off oxygen – and the fuel flexibility come in as paramount parameters that have to be given due consideration during the planning and procurement phases of the project.

Generally speaking, the best situation is when there is one major customer providing a base load for the system, a base load of a significant magnitude as compared to the total capacity. Such a base load may for example be a greenhouse or maybe the official buildings of the community, a school, a hospital or a sports centre or a major shopping mall.

Two crucial parameters:

To judge the feasibility of a district heating systems, two major parameters should be evaluated, namely the *areal energy density* and the potential *line load.*

The *areal energy density* is simply the total heating needs (for example measured in MWh/year) divided by the physical, geographical, size of the area where the energy measurement has been done. If, for example, a 1.5 km^2 portion of a residential area would have an annual heat consumption of 5 GWh, then the specific areal energy density becomes $5GWh/1.5km^2 \cdot year$ or $3.75\ kWh/m^2 \cdot year$. For Swedish conditions, this would be considered a low number, 5 or higher would be more normal, but it would not be extremely low. Suppose now that the areal can be shifted to accommodate also a shopping mall. Maybe the area then becomes 2.3 km^2 instead, but because of another group of houses and the shopping mall, the total heat consumption now is 17.5 GWh, raising the specific energy density from 3.75 to 7.6.

The *line load* is a similar measure – but instead of reflecting the areal density it will reflect the piping. The line load is simply the total energy distributed divided by the total length of the distribution network. Looking again at the above example, one may assume that in the first case (5 GWh/1.5 km^2) there might be about 4-500 individual households, separate maybe 40-50 m. Assuming then 100 m (forward and return tubing) for each household, would imply a total piping of about 40-50 km, say 45. Add 5 km for the piping to connect the boiler and the line load of the system would then become 5GWh/50km or 100 kWh/m•year. This is a very low value and the consequence of such a low line load is that piping losses will become very large in this system. To be really feasible, you would prefer line loads exceeding 300 kWh/m•year but 200 might also be acceptable. In the second example, we might use 80 km just to calculate the line load and one finds 220 kWh/m•year.

Changing the location of the boiler or maybe re-structuring the grid to minimize pipe length, will affect the line load while the energy density remains constant.

In some cases – like if the district heating system could be fired with a fuel having a negative price (*one might well be paid to use municipal waste for fuel*) – then energy density and line load might be of no significance, but it there is a cost for the fuel, then the energy density and the line load will put demands on the fuel price. A long-term demand for a low fuel price may, in turn, be met by accepting an increase in the investment cost, so that a fuel flexibility is built into the system already from the beginning…

Limits to the combustion process

Any fireplace is designed to work best with a specific fuel at a specific firing rate (i.e. thermal output). Good combustion equipment – fed with the correct fuel at the correct rate – will provide a complete burnout of the fuel in combination with minimal amounts of air pollutants. As already pointed out in chapter 00-01, the combustion process is an intricate combination of aerodynamics, heat- and mass-transfer, and chemistry.

With a larger boiler, like what is needed for district heating applications, it becomes possible to employ not only advanced and computerized combustion control but also fuel gas cleaning. Such polishing of the environmental performance of the combustion process improves the possibilities to switch fuel and hence to utilize the fact that different fuels will have different prices at different times. But there are limits to the flexibility:

- With a moving-grate boiler the fuel particles are mechanically transported along the grate by aid of the periodic movement of the fire grate bars. This means that the particle residence time in the combustion zone is set to some interval and that too small particles will not make full use of the grate length while too large particles will not be able to burn out completely. The same thing applies to variations in moisture content: too dry particles will burn too fast while too wet fuels will not be able o burn out completely.
- The amounts of ash in the fuel, together with the ash melting behaviour, will also impose limits to the possible fuels.
- The aerodynamics of the combustion process impose another type of limitation: as the demand for thermal power is reduced, so is the amount of combustion air supplied to the boiler. The combustion air is the agent that carries the kinetic energy to stir and mix the gases in the combustion volume and the kinetic energy is reduced in proportion to the square of the flow rate. Hence; as the boiler is turned down to half load, the kinetic energy for mixing is reduced to only 25 % of that at full load – and the quality of the mixing becomes worse. This, in combination with the lower temperatures experienced during turn-down, sets a lower limit to the thermal load of the boiler, typically at 1/3 or 1/4 of the

nominal capacity. For summer load and low-load periods it may be wise to install an extra boiler unit of a smaller scale in parallel with the main unit. A common way to do this in Sweden is to install a small wood-pellet boiler in parallel to the main wood-chips fired boiler.

- In peak-load situations, the residence time for the gases inside the combustion chamber may become too short for a complete burnout. Again, a complementary, small boiler may provide the solution.

Thus, the boiler setup for a flexible system might for example consist of:

- A wood-pellet boiler with a maximum thermal capacity about 30 % of the peak load demand. With a turn-down ratio of 1:3, this boiler will be able to supply the system at low load situations, 10-30 % of peak load demand.
- A moving-grate boiler designed for the most common fuel in the region – but with a feeding system and a process control laid out to facilitate good combustion of a number of other fuels as well. With a nominal capacity of this unit set at about 70-75 % of peak load and a turn-down ratio of 1:3, this boiler will be the base load unit covering the span from about 25 % and all the way up to 70-75 % of the thermal load demand. So the low end of the base-load boiler control span overlaps the high end of the low-load boiler capacity.
- At peak load situations, both boilers are run simultaneously, covering the peak load demand.

Relevant standards

At this scale there are no standards available for the boiler design but one is dependant on individual designs made by the manufacturers. However, EN 15316-4-7 covers the dimensioning methods for building heating systems and may prove helpful to dimension the customer heat exchangers.