Distribution technologies for LTDH/HTDC

In this article, different aspects of distribution-side technologies for LTDH and HTDC are discussed.

Distribution losses

The distribution loss can be related to the energy supplied to the networks, which gives relative heat loss. In western and northern Europe the relative heat losses are 8-15% and in eastern Europe 15-25%; see the textbook by Frederiksen & Werner. The effect of changing the temperatures in a given network can be estimated quite easily, since the heat losses are proportional to the temperature difference between the pipes and the surroundings. When the pipes are buried in the ground, the ground temperature can be set to the average outdoor temperature.

Examples

In a district heating system where the supply temperature is 80 °C, the return temperature is 45 °C and the average outdoor temperature is 10 °C, the average temperature difference is (80+45)/2-10=52.5 °C. If we manage to lower the return temperature by 5 °C, the average temperature difference becomes 50 °C, i.e. almost 5 % lower. Thus, the distribution losses will also be reduced by 5 %. If this network could be operated as a low-temperature network with 55/25 °C, the average temperature difference would be 30 °C, and the distribution losses will become 43 % lower. This estimation is valid when the same pipes are present in all cases, i.e. when the temperature is the only parameter that may change. When planning a new network, the calculation must take into account the pipe characteristics, since the temperature levels will affect which pipes are chosen.

Pumping energy

Distribution losses are also related to the energy needed for pumping the water in the network. If we again have the flow temperature at 80 °C and the return temperature at 45 °C, a decrease of the return temperature by 5 °C implies that the same delivered heat can be done by using less transported water. The temperature difference is increased from 35 °C to 40 °C, which is a 14% relative increase. The pumping energy is approximately proportional to the cube of the flow, but about 75% of the pumping energy will become heat useful for the customers; see the report by Selinder & Walletun. This means that the relative pumping energy becomes (1-0.14)3 = 0.64. Hence, the electricity needed for pumping has decreased by 36%, but 75% of that energy has had to be replaced with thermal energy (heat).

Design of district heating pipes

There are various types of district heating pipes. In this section we summarize the most common and give a table of their cost.

Straight district heating pipes

District heating distribution networks for high operating temperatures should endure 120 °C continuously during 30 years, see EN253. Occasionally the temperature may go up to 140 °C. Traditionally these systems have been built up of a service pipe of steel (P235), which is insulated with polyurethane (PUR) and protected (enclosed) by a casing pipe of polyethylene (HDPE). The operating pressure in the system may go up to 25 bar. These kinds of pipes belong to the third generation as defined by Frederiksen & Werner; see also the Chapter Introduction/Background. Pre-insulated straight district heating pipes can be manufactured with different insulation thickness called Series 1, 2, 3 and 4. The diameter of the casing pipe increases with number of the series, and more polyurethane is used for filling the space between the service pipe or pipes and the casing pipe.

Flexible district heating pipes

When the operating temperature can be decreased, other material can be used in the service pipes. There are flexible district heating pipes with different kinds of service pipes, see EN1532-1. There are metal service pipes of mild steel, copper or corrugated stainless steel. For these types of service pipes, the same temperature levels can be used as for the traditional pre-insulated pipes previously mentioned. When the operating temperature in general is less than 80 °C, but occasionally goes up to 90 °C, plastic service pipes can be used. The material cross-linked polyethylene (PEX) or polybutylene (PB) are used in service pipes of different wall thickness at the operating pressure ranging from 6 bar up to 10 bar, see EN15632-2. There is also an option to use multilayer plastic service pipes. Compression fittings are used for connecting the ends of the service pipes. The diameters of the service pipes for 6 bar available on the market are in the range from 20 to 110 mm. Also, the flexible pipes are also built up of a service pipe, insulation material and a protective casing pipe. Aquawarm is a flexible district heating pipe with service pipes of copper, insulation of mineral wool and a corrugated casing pipe of polyethylene (HDPE), see www.aquawarm.com.

Insulation materials

Furthermore, when a low operating temperature is used, other insulation materials than polyurethane can be used. Hence, thermoplastic polymers can be used instead of the thermosetting polymer polyurethane. There are at least two types of insulation materials used in flexible pipes on the market: polyurethane or polyolefin, see, eg, www.logstor.com and www.thermaflex.dk. Examples of thermoplastic polyolefins are polyethylene (PE) and polypropylene (PP). It must be possible to manufacture foam for creating a useful insulation material. There have also been studies on behaviour of carbon dioxide blown polyethylene terephthalate (PET) foam as insulation material in district heating pipes; see the paper by. This type of foam can also be used when the operating temperature is less than 100 °C. However, the foam must be produced and applied effectively in the pre-insulated district heating pipe. This might be one reason why this pipe design not was put on the market after the research project was completed.

Insulation of expanded polystyrene

There is an alternative to the conventional solution with a protective casing pipe on the market. The service pipes of PEX are insulated with blocks of expanded polystyrene without any additional protection, see www.elgocell.se. This design can be used when laying pipes in trenches.

Twin and triple pipe designs

Dalla Rosa et al. compared different designs of district heating pipes. Asymmetric twin pipe designs have been evaluated and the focus has been to decrease the losses of the supply pipe as much as possible, see Figure 28. For a DN20 Aluflex design, the losses from the supply pipe placed in the centre of the casing was about 4 % less compared to the conventional symmetric twin pipe design, but the total losses were more or less the same. For larger dimensions the circumference of the supply pipe was placed at the centre of the casing pipe. For a DN65 the losses from the supply pipes decreased about 8% and the total losses decreased by about 3 % compared to the symmetrical twin pipe design. Also triple pipe designs were evaluated, where there are three pipes: one supply pipe, one return pipe, and a third pipe for supply and recirculation. The latter pipe design is intended for low-energy applications where heat exchangers produce domestic hot water instantaneously.

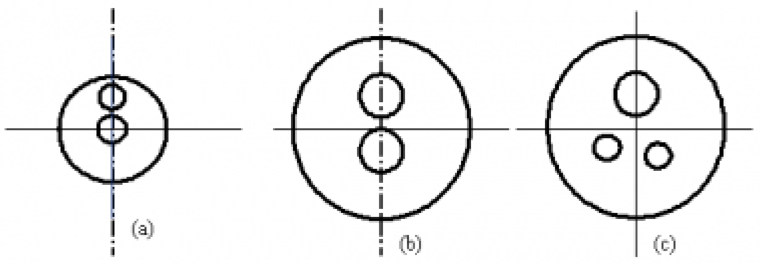

Figure 1 Principle sketches of pipes cross-sections investigated by Dalla Rosa et al. (2011a).

Costs of piping materials

Cost estimates of installation of district heating pipes in Sweden have been published by the Swedish District Association. Costs of a selection of district heating pipes of comparable dimension are given in Table 2.

Table 2. Cost estimates of selection of district heating pipes.

Pipe type	Dimension [mm]	Sum material & works excl soil works [EUR/m]
Aquawarm single	28	55
Aquawarm twin	28	52
Straight traditional single	25	40
Straight traditional twin	25	33
Flexible single	32	36
Flexible twin	32	38
Aquawarm single	54	88
Aquawarm twin	54	81
Straight traditional single	50	54
Straight traditional twin	50	51
Flexible single	50	48

Overview of district heating pipes

In Table 3, the possible types of district heating pipes are given based on the continuous maximum flow temperature.

Table 3. Possible types of district heating pipes available for different temperatures.

Supply temperature	DH-pipes	Insulation
120 °C	Traditional straight DH-pipes with service pipes of steel	Polyurethane
120 °C	Flexible DH-pipes with service pipes of mild steel, copper or corrugated stainless steel	Polyurethane
120 °C	AQUAWARM with service pipes of copper	Mineral wool
80 °C	Flexible DH-pipes with service pipes of PEX or Polybutylene	Polyurethane or polyolefin (e.g. polyethylene)
80 °C	DH-pipes built up of service pipes of PEX and blocks of insulation	Blocks of expanded polystyrene

Low energy networks

Dalla Rosa & J E Christensen concluded that low energy networks can be cost-effective and environmentally friendly in areas with a linear heat density as low as 0.20 MWh / m year. The definition of the linear heat density is the total annual heat sold divided by the total trench length of the network . They also showed that low-temperature operation is superior to low-flow operation, when comparing the annual primary energy needed for a set of network designs. Tol & Svendsen proposed a new dimensioning method for low energy districts, where the heat losses are minimized rather than the pipe dimension based on acceptable pressure drops. They stress that, for each pipe segment, the degree of simultaneity of the heat customers involved has to be considered. In their study, they also concluded that buffer tanks for domestic hot water at the substations reduce the pipe dimensions. Large temperature drops in low energy district heating networks can be avoided by using bypasses from flow to return lines. Also, further reduction of pipe dimensions can be achieved by increasing the flow temperature at peak loading in the winter. Li et al. introduced the concept of supply water recirculation with an additional service pipe. The purpose is to maintain the supply temperature at an acceptable level during low heat demand in the summer without increasing the return temperature, which would occur with a by-pass to the return pipe. The third pipe going from the plant to the junction in the street can be designed for recirculation in the summer period only or for recirculation in the summer and as a supply line in the winter period. The latter alternative gave the largest network heat loss. For instantaneous heating of domestic hot water by use of a heat exchanger, the design supply temperature was 55 °C and the design return temperature was 22 °C. The by-pass temperature was set to 50 °C. The third pipe means that the return temperature can be maintained a low level and in their case at 22 °C. When the by-pass to the return pipe was applied the return temperature increased to as much as 36 °C in their case. The recirculated water was kept above 44 °C.

Installation methods

All types of district heating pipes can be laid in open trenches. In general, pre-insulated district heating pipes can be installed by use of directional drilling. Flexible pipes can also be laid in very narrow trenches. In green areas ploughing techniques can be used with integrated digging, laying and refilling. A way to decrease the investment costs is to install different kinds of infrastructure simultaneously. The installation becomes more rational, but maintenance costs may be affected negatively, see the report by Gudmundson Shallower burial of water and sewage pipes may also be possible when district heating pipes heat those pipes and decrease the risk of freezing. In Västerås in Sweden, simultaneous installation of water, sewage and district heating pipes have been applied, see Andersson. A low temperature district heating network was installed as a secondary network supplied with heat from the primary network by use of a heat exchanger. Improved planning of installation works can also bring down installation costs as well as more standardized components for low temperature systems, see the report by Lauenburg.

Deterioration of polyurethane

The deterioration of the adhesion of the polyurethane towards the steel service pipe is governed by an Arrhenius relationship according to EN253. The activation energy is given to Ea = 150 kJ/mol, but there is a statement in the standard that this value has to be confirmed in further studies. The reaction speed can be expressed as

$$k_1 = A_0 \exp[- \frac{E_a}{RT_1}]$$

Where ideal gas constant is denoted R = 8.314 J/K mol, the temperature is T_1 [K] and A_0 is a constant. When the flow temperature is decreased from 100 °C to 80 °C, the Arrhenius relationship with the given activation energy reduces the reaction speed by 15 times.

Smart district heating networks

Brand et al. introduced the term prosumer in smart district heating networks. The prosumer is both consuming and producing energy. When the operating temperatures decrease, decentralized renewable energy sources can be introduced into the district heating networks with base production from a conventional plant. The introduction of these renewable energy sources is essential for creating sustainable energy systems. The energy can be supplied from solar collectors, industrial processes, or heat pumps. In general, water temperatures in the networks decreases when decentralized renewable energy sources are introduced. Hence, the decreased temperatures call for larger flows for delivering the same amount of heat. When the water from the decentralized source can be mixed with the water from the conventional plant, the differential pressure between the flow and return line will decrease. However, when the prosumer generates its own pressure cone, the differential pressure will increase. The introduction of prosumers calls for reinvestigation of the complete distribution system, and increased demands on control and management of sources, as the differential pressure affects all parts of the system.

Water hammer

A district heating network is a closed thermohydraulic system in which a multitude of valves, pumps and other equipment is present in direct contact with the district heating water. Temperatures up to 120 °C and pressures of up to 16 bars are not uncommon in district heating systems in periods of high heat demand. Should pipes or other components rupture and expose the surroundings to district heating water, the high temperatures and pressures pose a considerable risk. It is therefore of high importance to maintain adequate temperature and pressure regulation in the district heating system. Under pressures as well as overpressures may result in pipe failures, component damage or leaks.

Any operational change which results in a change in velocity or pressure, such as starting or stopping a pump, results in a pressure transient that propagates in the form of a wave in the district heating system. A distinct pressure transient in a piping system is known as a water hammer and can be triggered through several mechanisms. Water hammers in the district heating distribution system pose a risk for the supply security of district heating, as high peaks in pressure can rupture pipes or damage valves or other components in the district heat distribution system.

An assessement of a number of accidents (with damage to property or person) related to district heating systems concluded that water hammers or elevated pressures are among the most common causes of accidents in district heating distribution systems. In order to secure the supply of district heating, it is necessary to find a strategy to minimize the occurrence of water hammer incidents.

The following sections will briefly discuss water hammers in district heating distribution networks. However, water hammers in production systems also pose a risk for the supply security of district heating. Steam piping in a CHP plant is an example of this: interruptions in these piping systems may cause plant downtime which reduces the supply of district heating from a given plant. Damages due to water hammers in these systems may therefore ultimately interrupt the supply of district heating.

Joukowski pressure peaks

Damages to a float gauge caused by a Joukowski pressure peak. Photo by CEphoto, Uwe Aranas (link)(CC BY-SA-3.0).

When a valve is rapidly closed or a pump is rapidly stopped, a water hammer in the form of a Joukowski pressure peak is created. This water hammer propagates in the reverse direction of the flow. For example, when a valve is closed rapidly, the kinetic energy of the water upstream the valve is converted to pressure due to the inertia of the moving water. The pressure increase in the fluid can be significant and expands the surrounding pipe section. The pressure wave then travels upstream the pipe and may damage components if the pressure exerted exceeds that of the design pressure. The Joukowski pressure peak can be expressed according to the following equation (adapted from):

$$\Delta p = \rho a \Delta v$$

Δp = Magnitude of the water hammer pressure peak
ρ = Density of the liquid
a = Speed of sound in the liquid
Δv = Velocity change of the liquid upon valve closure

Water column separation

Even though Joukowski pressure peaks can result in severe water hammers, most crucial to a district heating distribution system are low pressures which may in turn trigger severe pressure transients. Several mechanisms can cause water column separation, but all relate to creation and collapse of vapor cavities in a liquid-filled pipe. This is commonly referred to in literature as water column separation.

One mechanism of water column separation is due to the rapid closure of a valve or stopping of a pump. Initially, the district heating water is flowing at a constant velocity in a distribution pipe. When the flow is rapidly stopped, under pressure is built up on the downstream side of the closed valve or stopped pump. If the pressure falls to the extent that the saturation pressure is reached, vapor is formed in a cavity of increasing size. The surrounding pipe section is contracted. As the pressure is again increased, the vapor condenses. Since the volume of water vapor is less than 1/1000 of that of liquid water and the condensation of the vapor is very rapid, the vapor cavity collapses and is replaced by a near-vacuum in an instant. Surrounding liquid is drawn to the void due to the high pressure difference. As the liquid collides with itself and or the surrounding pipe section, an (often audible) hammer-like impact occurs. The surrounding pipe section is expanded. The impact results in a strong positive pressure transient which travels downstream along the pipe section with the speed of sound in the liquid. As the water hammer travels away from the valve, the pressure drops again and a new vapor cavity is formed. In this manner, repeated vapor cavity formation and collapse results in the formation of several water hammers. A water hammer event may therefore take place during a prolonged time period. The water hammers may, in addition, be influenced by reflections from previous pressure waves where a reflected wave can force a vapor cavity to collapse. The behavior of water hammers in a system is therefore difficult to predict accurately.

Water column separation in a district heating system need not be triggered by a rapid valve closure or pump stoppage if the water in the piping section in question is subjected to lower pressures than designed. One such situation where the risk for water column separation is present is in pipes at high elevation, e.g. in pipes delivering district heating to a house cluster on a hill. If the pressure is close to saturation pressure for the piping section and the flow is also subjected to a discontinuity such as a pipe angle, local water column separation may occur. This risk of this type of water hammer is higher in the outskirts of a district heat distribution system, as the pressures in these places may be lower.

Water hammer due to loss of pressure control

In contrast to the mechanism of water column separation, loss of pressure regulation can result in formation of steam even if the district heating water is static. If a section of the district heating distribution network is subjected to a lower pressure than intended, e.g. due to a pump failure, there is a risk of formation of steam.

If the pressure approaches the saturation pressure steam pockets are formed. When subjected to higher pressures e.g. in form of a pressure wave from the starting of a pump, the cavity condenses rapidly and collapses. If there is a loss of pressure regulation and a simultaneous loss of heat input to the district heating network there is a heightened risk of water hammer. This is due to the temperature loss of the district heating network over time. Steam pockets formed due to low pressure eventually condense as the temperature drops, resulting in a water hammer.

Slug-flow water hammer

In any piping system containing a mixture of vapor and water there is a risk of slug-flow water hammer. If a district heating distribution system experiences pressure below the saturation pressure of steam, such a mixture is formed. The risk is also present in steam systems with some amount of condensate. A vapor and water mixture does not flow evenly in a pipe. In systems with more steam than water (or condensate), the steam accelerates the water which forms a slug, travelling at the speed of the steam. In systems with more water than steam, pockets of steam tend to form. In both of these cases, steam easily flows past narrow passages such as angles or semi-closed valves. The following water slug does not, resulting in the water slug slamming into the component and exerting a high pressure. The mixing of steam and water should therefore be avoided in a pipe. District heating pipes should be adequately pressurized to prevent formation of steam and steam pipes should be adequately drained of condensate.

Propagation in the district heating system

When the pressure wave reaches any piping component which alters the flow, part of the water hammer is reflected back to the source. Tanks, reservoirs, valves or pipe bends are prone to reflect a water hammer. When the reflected water hammer reaches the source valve it is reflected again. In this manner, the water hammer travels back and forth between components. If the reflection of the water hammer is not partial but full, several distinct pressure peaks can be noted. In this case, the cycle of water hammer reflections is continuous and is only gradually dampened by friction in the liquid. As the water hammer is reflected with the speed of sound in the liquid, the reflection time is dependent on the length of the piping section and can be calculated according to the following equation:

$$T_r = \frac{2L}{a}$$

T_r = Reflection time from origin to reflection point and back
L = Length of piping section
a = Speed of sound in the liquid

The speed of sound in the liquid can be calculated according to the following equation:

$$a = \sqrt{\frac{K_{eq}}{\rho}}$$

a = Speed of sound in the liquid
K_{eq} = Equivalent elasticity module for all piping and liquid in the system
ρ = Density of the liquid

In order to avoid water hammers it is of interest to avoid creating any pressure waves, even if the pressure waves are within system design limitations. Pressure waves are superpositioned when they meet. Superpositioned negative pressure waves may result in a local pressure below the saturation pressure, resulting in a local underpressure with water column separation and water hammer.

Damages caused by water hammers

Water hammers are common, but most water hammer events do not lead to damage. Every component in the district heating distribution system has a certain design pressure, and as long as the water hammer does not exceed this no damage is done.

It is often difficult to correctly identify the root cause of an accident, failure or disruption in a district heating production or distribution system. One media-based study of the causes of accidents concerning district heating was made between the years of 1986 and 2009. In this study accidents, incidents and disruptions which were reported in media were documented. According to this study, water hammers were the probable cause of about 10 % of the reported accidents and incidents related to district heating production and distribution. This suggests that water hammers were the most frequent cause of interruptions and damage in district heating production and distribution systems, followed by explosions (9 %) and fires (7 %). Addressing the issue of water hammers should therefore be a priority in designing and operating any district heating distribution system.

Burst pipes. Photo by Chris Sloan via Flickr (link)(CC BY-2.0).

It is not uncommon that district heating substations are damaged due to water hammers. In the district heating system of Gothenburg the district heating substations of certain residential areas have been damaged by water hammers. Since damages to substations often influence only a minor part of the district heating consumers at a single incident, the damages to substations are not subject to major interest in media and are not documented to the same extent as more severe accidents. In addition, it is believed that only a small share of the cases of substation breakdown are correctly identified as being caused by water hammers. The real number of water hammer incidents leading to substation damage may therefore be greater than what is known.

In rare cases the effects of a water hammer may be severe, as was the case in an interruption in the supply of district heating in Södertörn, south of Stockholm in 1980. Due to the commissioning of a new pump for the district heating distribution network, a distribution pipe burst and an expansion vessel was damaged. Due to the damages to the expansion vessel, the distribution network could not be correctly pressurized after reparation of the distribution pipe was completed. The reparation work of the expansion tank lasted four days during a period of outside temperature close to 0 °C. As a result, heat consumers were forced to use their domestic cooking ovens to maintain adequate indoor temperature which brought a severe strain on the local electricity distribution grid.

Preventing water hammers

Water hammers can be prevented in several ways, in the chapter below some strategies on how to prevent water hammers are presented.

1. Slow regulation

A guiding principle in avoiding excessive pressure waves, pressure oscillation and related water hammers is to regulate pumps and valves slowly. The longer the total pipe length the longer the reflection time of the pressure waves in the system. A longer distribution pipe network therefore requires slower regulation. This will, however, result in longer periods of time when the pressures or flows in the network differ from the desired setpoint value. In large distribution networks this has to be tolerated. The control error need not cause a problem, however. As long as a sufficient differential pressure is maintained over the district heating substations heat delivery to the consumers is largely uninterrupted. In this manner, the risk of pressure oscillations and water hammers is traded for a control error which the heat consumer substations are let to handle.

2. Pressure regulation and water hammer dampening

If pressure waves or pressure oscillations are created despite slow regulation, there are a number of effective countermeasures. One is to maintain adequate pressure levels throughout the distribution network, even after a pump faliure, through active pressure regulating devices. Pressure regulation through pumps or through compressed gas are examples of devices which can be applied. With an effective pressure regulation, adequate pressure can be sustained and steam formation can be avoided.

To protect a system from water hammers expansion tanks can be applied. When partially filled with gas and mounted in direct connection to the district heating water, the gas cushion acts to dampen the water hammer due to the compression of the gas. Expansion tanks have been applied in the district heating networks of Stockholm and Trollhättan to alleviate water hammers.

In order to alleviate the load of water hammers in the distribution network, Göteborg Energi has mounted numerous differential pressure valves across the distribution network. These devices have proven to be effective in reducing the occurrence of problems related to water hammer.

3. Pressure head symmetry

The symmetry of the pressure head in the district heating system needs to be considered when designing a district heating system. The pressure head should preferably be symmetric to avoid water hammers. A symmetric pressure head means that the mean pressure head is the same in the entire system. An asymmetric pressure head increase the risk of water hammers at pump shutdowns. Both the inlet and return pipes in a pressure booster station should have pumps installed in order to create a symmetric pressure head. To maintain the symmetry it is necessary to start and stop the pumps at the same time which may be done by connecting the pumps electrically or by placing them on the same mechanical axis. However, it may be problematic to maintain a symmetric pressure head in cities with large differences in elevation throughout the district heating distribution network.

Read more

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  - Distribution technologies for LTDH/HTDC
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- Research conference paper: Improved maintenance strategies for district heating pipe-lines

External links

- Euroheat & Power Certification of pipes
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