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District heating in areas of low density

Optimum design of distribution and service pipes

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Optimum Design of Distribution- and Service Pipes

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SUMMARY

In order to keep district heating systems competitive in areas with single family houses, as well as in other areas with low heat demands, it is necessary to reduce the heat losses from the pipes. This reduction must be carried out as economically as possible.

The article analyses effects of media pipe dimensions and insulation geometrics. A comparison is made for different types of medium sized distribution pipes, as well as for different types for service pipes with respect to heat losses and to resource demands, i.e. works and materials needed for the casing and polyurethane insulation and the gravel in the excavations.

In the article we describe how the heat loss and the heat loss coefficients can be calculated, as well as the effect of heat exchange between the two media pipes on the return pipe temperature. The temperature dependency and the aging of the polyurethane insulation are briefly discussed.

Various pipe cross sections are considered, for instance double pipes (co-insulated pipes) with circular or egg-shaped casings, with equal or dissimilar media pipe dimensions, with symmetrical or asymmetrical placement of the pipes in the insulation. We also introduce the triple pipe with three different sized media pipes (two supply pipes and one return pipe).

In case of medium sized distribution pipes, an egg-shaped twin pipe reduces heat losses and excavation costs considerably.

In case of service pipes the triple pipe reduces the heat loss considerably. Dissimilar media pipe dimensions have advantages in case of pipes serving one, or maybe a few consumers, as the temperature loss in the forward pipe becomes important.

For the medium sized distribution pipe we found that an egg-shaped twin pipe can reduce the heat loss by 37% and the investments by 12% compared with a pair of single pipes.

For the service pipes we found that the triple pipe reduces the heat loss by 45 % compared with a common pair of single pipes, and by 24 % compared with circular twin pipes. The reduction in investment index is 21 %.

The article also addresses the question of the heat exchange between the two media pipes in a twin pipe. We found, that the return temperature has to be considerably lower than typical return temperatures today, if the return pipe is to be heated up by the forward pipe.

Key words:
Buried heating pipes; twin pipes; triple pipes; heat losses; insulation; costs, pipe design

Definitions:
Single pipe (-pair): Individually insulated pair of media pipes
Twin pipe: Co-insulated pair of media pipes of the same dimension
Double pipe: Co-insulated pair of media pipes of dissimilar dimensions
Triple pipe: Three media pipes co-insulated, two forward pipes, one return pipe
Asymmetric insulation: More insulation around forward media pipe than around backward media pipe – applies to all the pipe types above.

1 Introduction

During the last ten years there has been an increasing understanding in the Nordic countries for the necessity to reduce the heat loss from district heating networks in order to make district heating systems in low heat density areas competitive with other ways of heating. By low heat density areas, we mean line heat demands of approximately 2 GJ/year/m pipe length, typical for areas with single-family houses. This development is fortified by new building regulations that will reduce the heat demand further in the future.

This has led to improvements in pipe design, for instance to increase the insulation thickness, or to use two, three and four media pipes in the same casing. Also the thermal properties of the polyurethane foam have been improved by introducing micro cell foam and vapour barriers. The possibility to use some kind of vacuum insulation is also discussed, but is not presently on the market.

It should be noticed, that in Denmark with many single family houses connected to the district heating system, the total length of the service pipes can be equal to the length of the distribution pipes. Thus the heat loss in percentage of the heat production is high in many Danish district heating systems and it is very important to reduce the heat losses from the service pipes.

In this article we will show how the heat loss from advanced pipe systems can be calculated and we will compare the heat losses with traditional preinsulated single pipe systems. We will also discuss the internal heat exchange between the two media pipes in a twin pipe.

2 Steady state heat loss theory for buried heating pipes

In general the heat loss equations will be in the following form, Kvisgaard and Hadvig (1980):

Pipe j:

$$q_j = \sum_{i=1}^{n} p_{ji} (T_i - T_g) \qquad (1)$$

where
n is the number of pipes
q_j is the heat loss from pipe j
T_i is the temperature of pipe i
T_g is the undisturbed ground temperature
p_{ji} are system constants (heat loss coefficients).

In case of two pipes:

Pipe 1:

$$q_1 = U_{11} (T_1 - T_g) - U_{12} (T_2 - T_g)$$

$$= (U_{11} - U_{12}) (T_1 - T_g) + U_{12} (T_1 - T_2) \qquad (2)$$

Pipe 2:

$$q_2 = U_{22} (T_2 - T_g) - U_{21} (T_1 - T_g)$$

$$= (U_{22} - U_{21}) (T_2 - T_g) - U_{21} (T_1 - T_2) \qquad (3)$$

U_{ij} is the linear thermal transmittance, or the heat loss coefficient.

If we can assume that the heat flow from pipe 1 to pipe 2 is the same as the heat flow from pipe 2 to pipe 1, $U_{12} = U_{21}$, then the system constants are reduced to three constants. If pipe 1 is the supply pipe and pipe 2 is the return line, then usually $T_1 > T_2$, and $U_{12} (T_1 - T_2)$ is the heat flow from pipe 1 to pipe 2. Although the heat transfer appears to consist of two “independent” heat flows, it should be remembered that the actual heat transfer is two (or three)-dimensional.

In the case of twin pipes (two media pipes in the same casing) as well as single pipes of different dimensions, we need three system constants. In a typical case, the two single pipes are identical, placed horizontally and in the same depth from the ground surface. Then the system constants are reduced to two, $U_{11} = U_{22}$ and $U_{12} = U_{21}$. In this case the total heat loss is calculated from

$$q_{tot} = q_1 + q_2 = 2 (U_{11} - U_{12}) \left[\frac{T_1 + T_2}{2} - T_g \right] \qquad (4)$$

The quantity $2 (U_{11} - U_{12})$ is the quantity often supplied by the pipe manufacturers for horizontally placed identical single pipes. For other types of preinsulated pipe systems, U-values usually are not stated by the manufacturers.

For a triple pipe (3 media pipes in the same casing) we need nine system constants.

Pipe 1:

$$q_1 = U_{11}(T_1 - T_g) - U_{12}(T_2 - T_g) - U_{13}(T_3 - T_g)$$

$$= (U_{11} - U_{12} - U_{13})(T_1 - T_g) + U_{12}(T_1 - T_2) + U_{13}(T_1 - T_3) \quad (5)$$

Pipe 2:

$$q_2 = U_{22}(T_2 - T_g) - U_{21}(T_1 - T_g) - U_{23}(T_3 - T_g)$$

$$= (U_{22} - U_{21} - U_{23})(T_2 - T_g) + U_{21}(T_2 - T_1) + U_{23}(T_2 - T_3) \quad (6)$$

Pipe 3:

$$q_3 = U_{33}(T_3 - T_g) - U_{31}(T_1 - T_g) - U_{32}(T_2 - T_g)$$

$$= (U_{33} - U_{31} - U_{32})(T_3 - T_g) + U_{31}(T_3 - T_1) + U_{32}(T_3 - T_2) \quad (7)$$

However, this system can be reduced to six system constants, assuming $U_{12} = U_{21}$, $U_{13} = U_{31}$ and $U_{23} = U_{32}$.

3 Determination of heat losses and heat loss coefficients

Case A. Identical, circular, horizontally placed pair of single preinsulated pipes.
This pipe system is shown in Figure 1A. The U-values can be calculated with sufficient accuracy from analytical expressions, cf. for instance Bøhm (2000), bearing in mind the uncertainty associated with the material properties, cf. below.

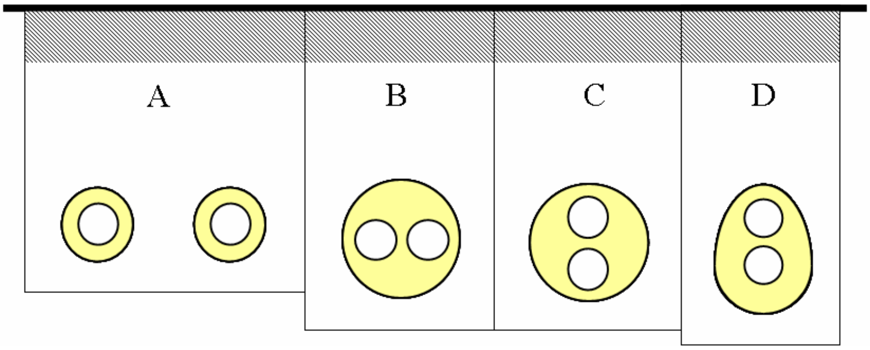

Figure 1. District heating pipe systems. A: Pair of single pipes. B: Horizontal twin pipe. C: Vertical twin pipe and D: Egg-shaped twin pipe. The boxes around the pipes indicate the size of the trench.

Case B. Circular twin pipes with horizontally placed identical media pipes.
This pipe system is shown in Figure 1B. In this case, an approximate solution to the Multipole method has been derived by Walletén (1991).

Cases C and D. Other pipe systems (Circular and non-circular twin pipes, triple pipes)
These pipe systems are shown in Figures 1C and 1D. For circular pipes and casings, the Multipole method developed by Claesson and Bennet (1987), can be used to calculate the heat loss.

However, in the general case the heat loss must be obtained by use of numerical methods, for instance the finite element method. In order to find the heat loss coefficients, different temperature sets must be used and next the n-equations with n unknown must be solved, cf. equation (1). Alternatively, the heat loss can be calculated for some temperature sets where U-values are obtained directly. For instance to find (U_{11} - U_{12} - U_{13}) in equation (5), the heat loss can be calculated for the case T_3=T_2=T_1.

4 Material properties

In some cases the heat loss from a new pipe is desired in the design phase, in others the heat loss from pipes in operation for many years is desired. The thermal properties have a big influence on the heat loss calculations and especially in the latter case it is difficult to estimate the thermal conductivity due to possible degradation and ageing of the foam.

Although the thermal conductivity of the surrounding soil is difficult to estimate due to inhomogeneous and partly unknown soil composition and moisture content, the soil conductivity will usually play a minor role for modern, preinsulated pipe systems (we use a value of 1.5 W/(m·K) for the soil thermal conductivity in the following calculations).

The thermal conductivity of the (polyurethane) insulation on the other hand has an almost proportional influence on the heat loss. The thermal conductivity depends on the temperature and moisture content as well as on the ageing of the foam, cf. Figures 2 and 3. Especially for CO_2-blown foam, which was used in the 1990'ties before cyclopentane was introduced, we see a significant change of the thermal conductivity after just a few years. Figure 2 also shows that the use of a diffusion barrier effectively hinders the ageing process.

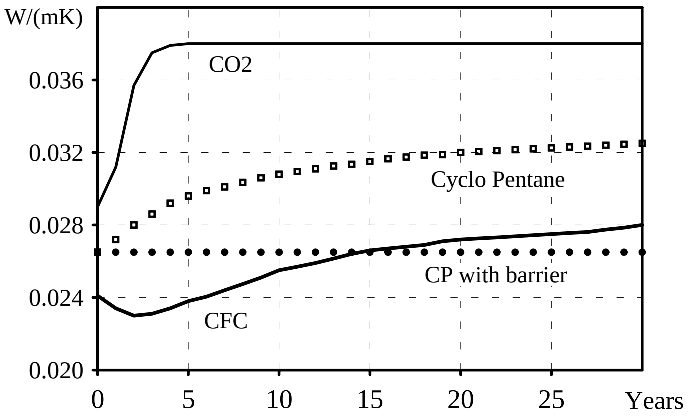

Figure 2. Calculated change of the thermal conductivity with time for different polyurethane foam types: CO_2, Cyclo Pentane, Cyclo Pentane with diffusion barrier, CFC (Difluoro-Dichloro-methane). Example case (diameter of steel pipe and casing not stated). Smidt (2002).

Usually the thermal conductivity at 50 ˚C is stated by the manufacturers. To illustrate how the thermal conductivity of polyurethane insulation depends on temperature, Figure 3 shows one example, Alstom (2004).

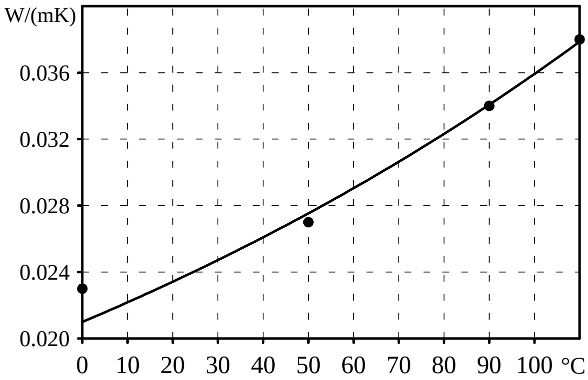

Figure 3.Thermal conductivity of polyurethane foam as a function of temperature, Alstom (2004).

Sometime manufacturers state that the temperature dependency makes it less convenient to use U-values and therefore numerical simulations must be applied. Nevertheless U-values are convenient in many situations, for instance to calculate the heat exchange between the two media pipes, cf. below. An estimate of the error introduced by the temperature dependency is described in the following.

In case of radial heat transfer through the insulation, the heat loss is calculated from:

$$2\pi \int_{T1}^{T2} \lambda(T)\, dT \quad = \quad -q \int_{Dp}^{Di} \frac{1}{x}\, dx. \qquad (8)$$

where λ is the thermal conductivity of the insulation, x is the radial distance from the pipe wall and T is the temperature.
For constant λ, we get the well-known result

$$q \quad = \quad 2\pi\lambda (T_p - T_i) \;/\; \ln(D_i / D_p), \qquad (9)$$

where D_i and D_p are the diameter of the insulation and the steel pipe, respectively.

T_p and T_i are the temperatures of the pipe wall and the exterior of the insulation, respectively.

As a simple approximation to the curve in Figure 3 we can use the expression

$$\lambda \quad = \quad 0.023 \cdot \exp(0.005 \cdot T) - 0.002, \quad \text{for } 30<T<110^{\circ}\text{C} \quad [\text{W/(m}\cdot\text{K)}] \qquad (10)$$

Equation (8) can now be integrated directly, and this heat loss can be compared with a solution with temperature independent thermal conductivity. For the single service pipe, see below, the error was approximately 2%. We found that instead of evaluating the thermal conductivity at the mean temperature, it should be evaluated slightly above the mean temperature to eliminate the error. Taking the temperature dependency into account in this way, we recommend that U-values be used to characterize the heat loss from buried pipes. However, it should be kept in mind that U-values are dependent on temperature as well as on time (ageing of the foam).

5 Investment in the pipe network

The investments in a new pipe network consist of the production costs of the pipe itself, the component costs (branch tees etc.) which depend on the network structure, and the cost of pipe works and civil works. In this context we want to compare the costs of traditional single preinsulated pipe systems with the costs of using twin or triple pipes. The civil costs among other things depend on the pipeline space demand in the trench.

For calculating the investments, the following model developed in Kristjansson et al. (2004) was applied:

$$I_j = (\Sigma_i \, C_{ij}) \cdot F_j(G) + E_j \tag{11}$$

$$C_{ij} = P_i \cdot (M_{ij})^{0.8} \tag{12}$$

$$E_j = P_a \cdot (A_{aj})^{0.8} + P_g \cdot (V_{gj})^{0.8} + \text{constant} \tag{13}$$

where

I is the investment in pipe network
j is a pipe dimension index
i is a material index (steel, casing, insulation, etc.)
C is cost of straight pipeline
F is a cost factor of components, depending on the network structure index G
E is the excavation costs
P is a material price factor (incl. work)
M is the volume of pipe material,
A is the area of asphalt of the trench
V is the volume of gravel in the trench.

All parameters including the power factors of 0.8 were found with a good correlation from multivariable regression of data from actual projects. Investments in new pipe geometries not installed yet were predicted by the above model.

We will use this cost model in the following two examples. The model gives consistent results with the findings in Schmitt and Hoffmann (1999). Here savings of 15 % to 19 % were found by using twin pipes compared with horizontally placed single pipes for German and Finnish conditions.

6 Investment and heat losses – two examples

In the following we will demonstrate how U-values can be calculated and we will quantify savings by using an advanced pipe design compared with traditional design. To this end we will consider a distribution pipe and a service pipe.

6.1 Medium sized distribution pipe

We will choose a 80 mm pipe as a typical medium sized distribution pipe. This pipe has a capacity of 800 kW (at 100 Pa/m and 40 K temperature difference), capable of supplying approximately 80 single family houses with heat. We will evaluate the heat losses at supply and return temperatures of 80 and 40 ˚C, respectively, and a ground temperature of 8 ˚C.

For twin pipes we will assume that the media pipes are placed vertically with the return pipe located closest to the ground surface. This gives the lowest heat loss compared with having the supply pipe on top and compared with horizontally placed media pipes.

How can we make a fair comparison of heat losses from different pipe systems and how can we take different investment costs into account? In a comparison of single pipes and twin pipes (circular and ellipsoidal), Jonson (2001) assumed that the same amount (volume) of insulation must be used in both pipe systems. However, here we will assume that ellipsoidal and egg-shaped profiles must be made from circular casing pipes available on the market.

The thermal conductivity is assumed to be 0.0265 W/(m·K), representing present standard of new polyurethane foam for straight pipes.

The following pipe systems are considered:

A. Pair of single preinsulated pipes ø80/160 with D_p = 88.9 mm, D_i = 157.8 mm.
B. Circular twin pipe ø80/80/250 with D_p = 88.9 mm, D_i = 248.3 mm. Distance between media pipes 25.1 mm.
C. Egg-shaped twin pipe 80/80/250 (Not commercial available).

The heat loss coefficients and the heat losses are shown in Table 1, obtained from analytical expressions in case A, the multipole method in case B, and the finite element method in case C.

Table 1. 80 mm (nominal) distribution pipe. Heat loss coefficients, heat losses, resources and costs.

DISTRIBUTION PIPE	HEAT LOSSES					RESOURCES			COST
	U_{11} supply W /(m·K)	U_{22} return W /(m·K)	U_{12} W /(m·K)	q_{tot} W /m	Relative loss %	Casing cm^2	Insulation cm^2	Gravel m^2	Investment index %
A Single pair	0.2664	0.2664	0.0113	26.53	100%	31	270	0.480	100%
B Circular twin	0.2517	0.2534	0.0784	18.08	68%	31	360	0.370	90%
C Egg twin	0.2264	0.2735	0.0799	16.74	63%	31	310	0.320	88%

Please observe that for circular twin pipes, the U_{11} and U_{22}-values for the supply and return pipes are very similar, although U_{11} is smaller than U_{22}. For twin and egg-shaped pipes, the U_{12}-value is high compared with the U_{11} and U_{22}-values, i.e. the heat exchange between the two media pipes is significant for these pipe systems in comparison with a pair of single pipes.

It appears from Table 1 that an egg-shaped twin pipe can reduce the heat loss by 37% compared with a pair of single pipes.

Table 1 also includes a comparison of the resources needed for the three different pipe systems with regard to casing, insulation material, and the amount of gravel in the excavation (ground coverage 0.5 m, side and base coverage 0.1 m, spacing between single pipes 0.15 m, cf. Figure 1). Even if the amount of insulation is bigger in the case of co-insulated pipes, the savings in component works and in the amount of gravel needed result in a cost reduction of 10% by installing circular twin pipes. Additional savings of a few per cent are achieved by using the egg-shaped twin pipe.

6.2 Service pipe

In this case we will consider both traditional single service pipes of cross linked polyethylene (PEX), two types of twin pipes and a new pipe design, the triple pipe with two forward lines and one return line, cf. Figure 4.

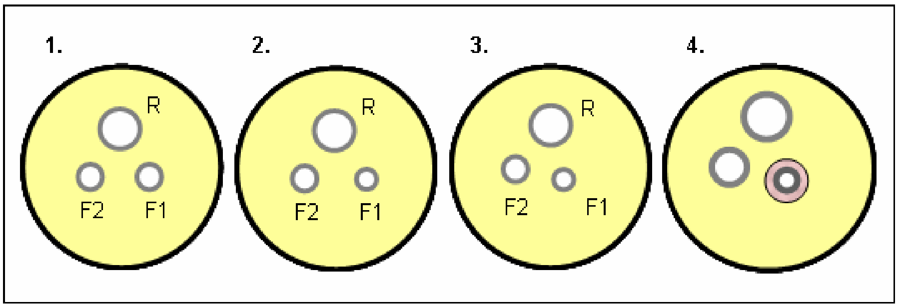

Figure 4. Triple service pipe in four versions, (1) even forward pipe dimensions, (2) dissimilar forward pipe dimensions, (3) … also asymmetrical placement of forward pipes, (4) super insulation on first priority forward pipe (future). F1: First priority forward pipe, F2 second priority forward pipe, closed most of the time, R, return pipe.

The basic idea of the triple pipe is that heat is supplied only by the smallest forward pipe in the normal case. When big heat demands occur, for instance when tapping of domestic hot water takes place, extra heat is supplied through the second forward pipe. It can also serve as a pure design reserve, which leads to designs with small pipe dimensions, saving heat losses.

The figure shows four different design versions of the triple pipe, depending on how optimized it is. In this section, we use version 2, the two forward pipes are of dissimilar dimensions which are both smaller than the return pipe, but the centres of the forward pipes are placed symmetrically.

The triple pipe not only has a smaller heat loss than traditional service pipes, but it also provides a better hot water comfort. The triple pipe can be combined with a booster pump in the house which can result in a reduction of media pipe dimensions compared with the dimensions considered below.

Investigated service pipes:
A1. Pair of single pipes ø20/66 (exterior diameters in mm)
A2. Pair of single pipes ø25/77
B1. Twin pipe ø20/20/90

B2. Twin pipe ø25/25/110
C. Triple pipe ø15/18/20/105 - second design version (not commercial available).

For the twin pipes and the triple pipe we will assume that the return pipe is located closest to the ground surface. The thermal conductivity is assumed to be 0.028 W/(m·K), based on polyurethane foam used for flexible service pipes. We will evaluate the heat losses at a summer situation with a (local) supply temperature of 60 ˚C and a ground temperature of 14 ˚C. When tapping of domestic hot water takes place, a return temperature of 20 ˚C will be assumed. When tapping does not take place, the return temperature is set at 50 ˚C. In this case, there is no flow in the second forward line of the triple pipe and its temperature is set at 32.3 ˚C ensuring zero heat flux.

The heat loss coefficients are shown in Table 2, obtained from the analytical expressions in case A and the multipole method in cases B and C. With these heat loss coefficients we can calculate the heat losses for the different temperature sets as shown in Table 3. On-going measurements on a triple service pipe in Denmark, Bøhm and Frederiksen (2004), show that the second forward pipe is only in operation for 1 hour per day (maximum). Therefore Table 3 also includes a time-averaged value for the heat loss. In the case of tapping of domestic hot water, the triple pipe has a higher heat loss than the twin pipe, but this situation is reversed when no tapping takes place.

Table 2. Heat loss coefficients for service pipes.

	U_{11} supply	U_{22} supply boost	U_{33} return	$U_{12}=U_{21}$	$U_{13}=U_{31}$	$U_{23}=U_{32}$
A Pair of single pipes						
ø20/66	0.1444		0.1444		0.0040	
ø25/77	0.1523		0.1523		0.0043	
B Circular twin						
ø20/20/90	0.1463		0.1465		0.0348	
ø25/25/110	0.1488		0.1491		0.0416	
C Triple pipe ø15/18/20/105	0.1197	0.1366	0.1471	0.0199	0.0377	0.0429

Many district heating companies in Denmark use the ø25/77 pipe as the normal service pipe and we will take it as the reference case in the comparisons. Compared with this pipe the triple pipe has a heat loss of only 55%. However, it can be argued that the ø20/66 pipe is a more fair comparison with the twin and triple service pipes as it has the same capacity as these. On the average the triple pipe reduces the heat loss by 24% compared with the twin pipes and by 40 % compared with the pair of ø20/66 pipes.

Table 3. Heat losses, resources and costs of service pipes.

SERVICE PIPES	HEAT LOSSES W/m				RESOURCES			COSTS
	No tapping 60/50 °C	Tapping 60/20 °C	Weighed with time	Relative loss %	Casing cm^2	Insulation cm^2	Gravel m^2	Investment index
A Pair of single pipes								
ø20/66	11.51	7.30	11.03	92%	8.3	54	0.297	96%
ø25/77	12.14	7.70	11.95	100%	9.7	74	0.316	100%
B Circular twin								
ø20/20/90	8.80	5.80	8.67	73%	5.6	52	0.186	73%
ø25/25/110	8.80	5.58	8.67	73%	7.5	78	0.205	79%
C Triple pipe								
ø15/18/20/105	6.61	6.65	6.61	55%	6.5	71	0.200	79%

In Table 3 a comparison is also shown of the resources needed for the different service pipe systems with regard to casing and insulation material and the amount of gravel in the excavation. Circular twin pipes result in a reduction in the investment index of 21-27 % compared with the reference case. For the triple pipe the reduction is 21 %.

7 Investment and heat losses – a more general approach

Recent information about savings obtained from twin pipes compared to single pipe pairs may appear to be somewhat confusing. Insulation classes of these two basic pipe types are not comparable because of different insulation cross section geometrics. A comparison between heat losses from different basic pipe types should take into account all costs and benefits of both pipe systems. In this case, the benefits are the heat loss savings while the costs are the resources used for production and installation.

7.1 Savings of twin pipes (equal media pipe dimensions)

In Figure 5, two series of PEX20-single pipes are compared to three series of PEX20-twin pipes. Each of the five series includes a range of casing diameters which makes up each of the five curves in the figure. All pipes have the same flow capacity and temperatures of 70/30/8’C (forward/ return/ soil). The curves show that an increase in casing size decreases the heat losses, but the reduction fades out with increasing casing sizes while the rate of resource requirements increases with growing rates. This sets an effective limit to the feasible extra insulation in case of each series.

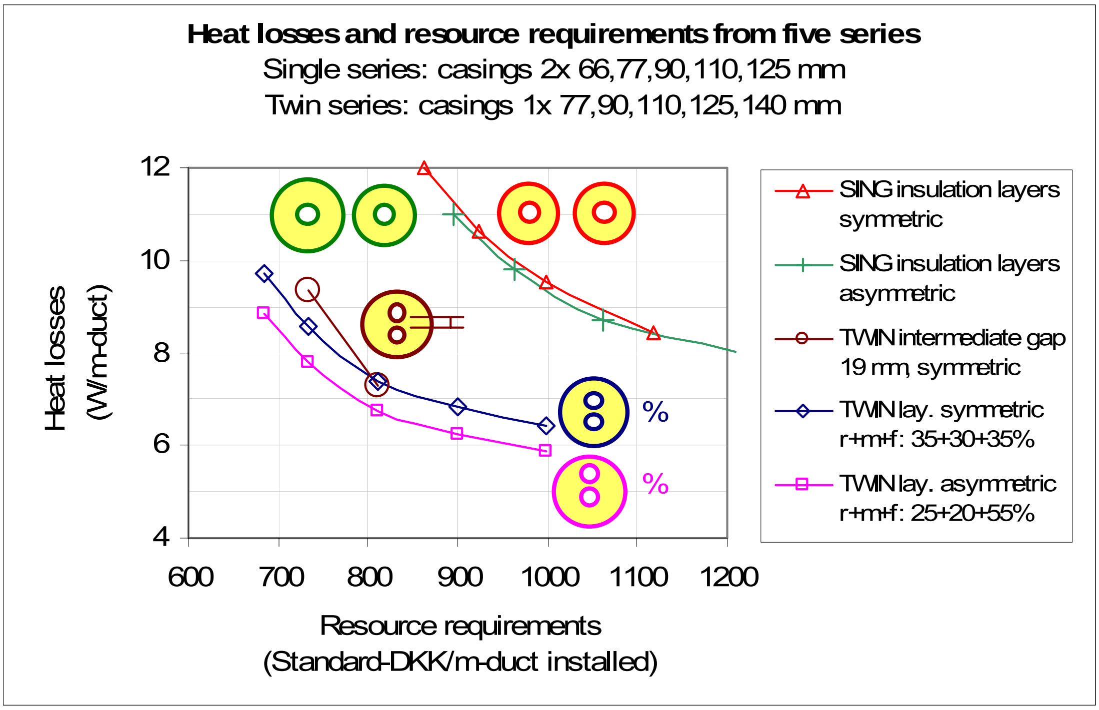

Figure 5. Heat loss from five series: 1: the traditional symmetrically insulated single pipe series with casings of 2 x 66, 77, 90, 110, 125 mm, 2: asymmetrically insulated single pipe series with forward casing one dimension up, 3: two twin pipes with casings of 1 x 90, 110 mm and symmetric insulation with 19 mm intermediate gap between media pipes, 4: twin pipe series with casings of 1 x 77, 90, 110, 125, 140 mm of symmetric insulation with intermediate gap of 30% of all three insulation layer thicknesses (pipe gaps) together, and finally 5: same twin pipe series but with asymmetric insulation with layer thicknesses in the ratios 25+20+55% (return side gap + intermediate gap + forward side gap).

The first of the two single pipe series in the upper part of the figure includes standard insulation on both media pipes while the second series includes extra insulation of the forward pipe, saving more than 10% of the heat losses, moving the curve downwards. But simultaneously, the curve is moved to the right because of the increased resource requirements, limiting the net savings to an insignificant level as can be seen from the fact that the two curves are almost on top of each other.

The short curve in the figure shows the commercial PEX20 twin pipe with the casings of 90 and 110, respectively, which both have the same media pipe gap of 19 mm - media pipe gaps have been kept in standard figures as far as possible for practical reasons.

A more general version of the twin pipe with the total range of casing diameters is represented by the next curve below. Here, the gap is adjusted in accordance with the fact that the relative ratio of heat loss to heat fluxes strongly depends on the relative placement of the media pipes inside the insulation. In this series, the *relative* cross section geometry is kept the same for different casing diameters, with a relative thickness of the three insulation layers of 35+30+35% (return side gap + media pipe gap + forward side gap).

A *vertical* comparison between this twin pipe curve and the single pipe curve leads to the conclusion that the twin pipe *in principle* and in rough numbers saves 40% of the heat losses (PEX 20 mm). However, savings obtained by increased casing diameters seem to fade out more sharply in case of twin pipes than in case of single pipes (depends on cross section design). Commercial conditions may limit the size of casings which may reduce heat loss savings to a smaller figure than indicated above, but then this saving reduction is converted into investment savings.

The last and nethermost curve represents a twin pipe with asymmetric insulation with a thicker insulation layer around the hot forward pipe, obtained by replacing the media pipes inside the casing so the relative thickness of the three insulation layers is 25+20+55% (return side gap, intermediate gap, forward side gap). From the figure it appears that further savings of about 10% can be obtained, and this almost corresponds to a whole insulation class (casing diameter). These savings are relatively independent of the casing diameter.

Another argument for using asymmetric insulation of twin pipes is that less than half of the savings of twin pipes are obtained from the forward pipe. While most of the losses from the return pipe (symmetrical insulation) are saved (maybe 80%), savings of the forward pipe losses are more limited (maybe 30%) even though the total savings are 40%.

In case of service pipes, the temperature loss in the forward pipe is considerable, often 2-3’C. This supports asymmetric insulation of twin pipes.

7.2 Savings of double pipes (different media pipe dimensions)

Another method for reducing the heat losses from the forward pipe is to reduce the dimension of the forward pipe so the innermost and most important insulation layer becomes thicker around the forward media pipe. The production and laying costs stay at the same level, but now the water transport capacity of the pipe pair is reduced. A general comparison for most dimensions can be found in /2/, but here we focus on service pipes. The study starts with a PEX 20 mm and gradually reduces the dimensions of the media pipes to see the effects. The resulting plots of heat losses and the hydraulic capacity are found in Figure 6. The figure includes three groups of double pipes; the first group with media pipes of the same dimension, this is the twin pipe; the next group with a double pipe with forward media pipe one dimension less than the return pipe, that is (forward/return) 18/20, 16/18 mm, etc.; while in the last group, the forward pipe has a dimension two dimensions less than the return pipe (16/20, 14/16).

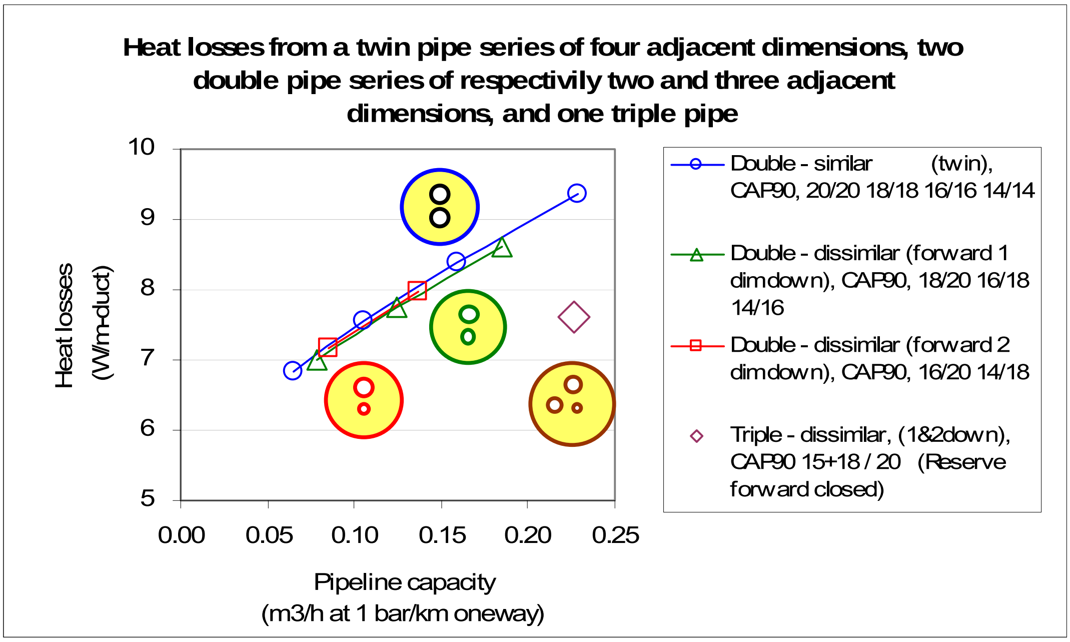

Figure 6. Heat losses from various designs of pipes where the designs affect the transport capacity of the pipes. All the pipes have the same casings, which in this case involves about the same resource requirements. The pipes compared are the twin pipe (similar pipe dimensions), double pipe (dissimilar pipe dimensions), with forward 1 dim smaller, double pipe with forward 2 smaller, and finally the triple pipe with three different and adjacent dimensions.

From the comparison between the three plots, it appears that *the principle* of using different media pipe dimensions does not lead to any noticeable savings, only a few percent (in the case of small pipe dimensions).

On the contrary, the figure also indicates that if double pipes are used together with twin pipes, the consequently better possibility of flow capacity adjustment may save up to 8 or 10% in individual cases, or maybe 4% in average for a large number of service pipes, and this opportunity of “cheap” savings should not be left out.

Another argument for a small forward media pipe dimension is that in case of small dimensions, especially as regards service pipes, the heat loss savings in the forward pipe also lead to temperature loss savings. This means higher comfort or less flow, and in critical areas of the network, these temperature savings should lead to lower supply temperature from the heat plant, which again reduces the heat loss in the whole network!

Temperature losses may also be critical in circumstances with uneven consumption (for example pure hot tap water usage). Less heat is lost when the pipe cools down during a night period without consumption, and small forward pipe dimensions cause the hot district heating water to reach the consumer faster (e.g. in the morning through the previously cooled down service pipe). It is though a canard that a small pipe dimension saves temperature owing to higher water velocity under static conditions. The reason is that a small pipe dimension also holds less water to cool, and these two geometric factors are of the same origin and counterbalance each other. Consequently, static temperature savings caused by reduced pipe dimensions are only possible because of heat loss savings.

All these conditions lead to the important conclusion that even if double pipes at first sight do not have advantages compared to twin pipes (in case of small pipe dimensions), the many side effects bring along considerable improvements. The asymmetrically insulated double pipe (which means dissimilar pipe dimensions) must be considered a better option than the symmetrically insulated twin pipe.

Finally, the previously introduced triple pipe has been plotted as a single point in Figure 6. Referring to Figure 4, it is in the third design version, which embraces an asymmetrical placement of dissimilar forward pipes, the smallest forward pipe is placed near the centre to the casing pipe. The figure indicates that the triple pipe becomes superior compared to other pipe designs, obtained by combination of sufficient capacity of a large pipe dimension and reduced heat loss from a small forward pipe dimension only in operation.

However, the point on the figure indicates the heat loss when only the small forward pipe is in operation, but the bigger forward pipe is also in operation few procents of the time. Therefore, the average heat losses will increase somewhat. Furthermore, dynamic operation conditions must be taken into account. It should be noted that the triple pipe cannot be applied to all consumer unit types, and this kind of pipe also has requirements as to the principal design of the consumer unit.

8 The heat exchange between the media pipes and the influence on the return temperature

It is sometimes argued that the return line in a twin pipe will be heated up by the forward line to an extent that is undesired. This question can easily be addressed by use of the heat loss coefficients.

In case of pipe system with two media pipes, the heat loss from the return pipe is (according to (3)):

$$q_2 = (U_{22} - U_{21})(T_2 - T_g) - U_{21}(T_1 - T_2) \tag{3b}$$

where U_{22} and U_{21} are heat loss coefficients, and T_1, T_2 and T_g are the temperatures of the forward pipe, return pipe and undisturbed ground, respectively.

U_{22} expresses the heat flux from the return pipe in case of no forward pipe, and U_{21} expresses the heat flux from the forward pipe to the return pipe.

U_{21} depends on the distance between the two media pipes as well as the thermal conductivity of the insulation material.

As a rough estimate for the magnitude of the two heat loss coefficients, the following figures can be given (in case of small pipe sizes):

For copper twin pipes: $U_{21} / U_{22} \approx$ 45-50%,
For cellular concrete ducts: $U_{21} / U_{22} \approx$ 35-50%, depending on moisture content
For PEX twin pipes: $U_{21} / U_{22} \approx$ 25%

For singular insulated pipes: $U_{21} / U_{22} \approx 3\%$

This means that the heat flux from the forward pipe to the return pipe may be expected to be relatively larger in case of twin pipes than in case of single pipes, and also larger in case of copper twin pipes than in case of PEX-twin pipes (by tradition, a shorter distance between the copper media pipes is applied).

In order to illustrate the amount of heat flux from the forward pipe to return pipe, let us consider the twin pipe PEX 20/20/90 (f/r/casing mm).

Figure 7 shows the heat losses when the distance between the two media pipes is increased from 0 to 46 mm. In the latter case, the media pipes are touching the casing pipe from the inside.

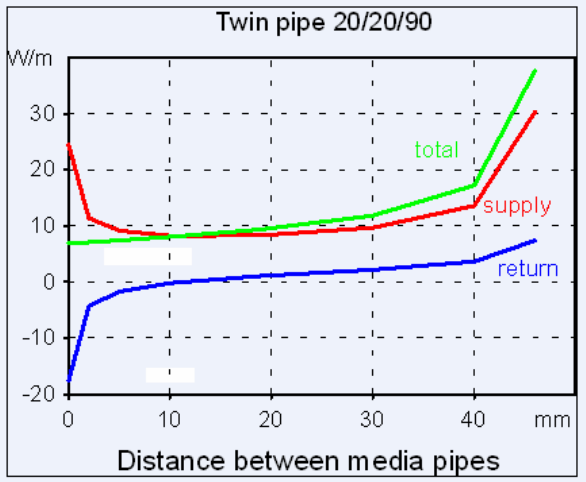

Figure 7. The distance between the media pipes influences the total heat losses (green), the forward pipe losses (red), and the return pipe losses (blue). Twin pipe 20/20/90 mm f/r/casing, temperatures of 70/30/8 °C f/r/soil, PUR insulation λ=0.028W/(mK).

The total heat loss as well as the heat loss from the return pipe increase with an increasing media pipe distance. If the distance is more than 10 mm, the heat loss from the return pipe is positive, which implies that the return line is not heated up. The total heat loss is minimized by minimizing the distance between the media pipes, but this situation is usually not feasible because of the large heat flux from the forward pipe to the return pipe, which causes an unnecessary temperature fall in the forward pipe and temperature rise in the return pipe.

The calculations are made for a thermal conductivity of 0.028 W/(m°K). PUR foam of considerably better quality is available on the market today, reducing all heat fluxes including heat exchange between the two media pipes.

In Denmark, the small twin pipes are often separated by a distance of 19 mm. Figure 8 shows variations in heat fluxes caused by variations in the return temperature when the forward temperature is kept constant. The net return pipe heat loss is equal to the heat loss from the return pipe to the surroundings minus the heat contribution from the forward pipe. The figure shows that if the return temperature stays above 23°C, then the heat contribution from the forward pipe is smaller than the return pipe heat losses to the surroundings, and therefore the return temperature will not increase.

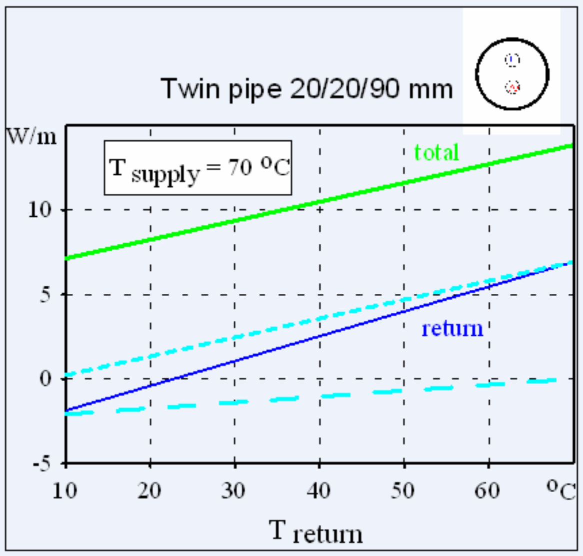

Figure 8. Heat losses at different return temperatures while the forward temperature is kept at 70’C. The total heat losses from both pipes are shown in green while the return pipe net heat loss (blue line) is the difference between the gross heat loss from the return pipe to the surroundings (upper dashed line) and the contribution of heat flux from the forward pipe (lower dashed line). Twin pipe 20/20/90 mm f/r/casing, PUR insulation λ=0.028W/(mK)

In general, the return temperatures in district heating systems stay within the range of 30-50°C, depending on load, consumer mix, etc. However, as to service pipes, the return temperature variations may be larger. As part of a research project sponsored by the Danish District Heating Association, measurements were carried out on service pipes in Nykøbing Falster. The measurements showed that the return temperature went down to 25-30°C for short periods, caused by hot tap water consumption.

It can therefore be concluded that the water in the return pipe of small sized PEX twin pipes is not heated by the forward pipe in general.

In case of medium sized pipes the results are similar to the ones shown in Figure 8, cf. /IJER/.

9 Conclusions

We have shown how the heat loss and the heat loss coefficients can be calculated for single, twin and triple buried heating pipes. The thermal conductivity of polyurethane insulation depends on temperature as well as on the time elapsed since the foam was produced (ageing) and we discuss how a representative value of the thermal conductivity can be determined.

We compared different pipe systems with regard to heat losses and the resources invested in works and materials and for excavation of the pipe. For the medium sized distribution pipes (ø89 mm), we compared a pair of single pipes with a circular twin pipe and with an egg-shaped twin pipe. We found that the egg-shaped pipe reduces the heat loss by 37 % and the investment index by 12 % compared with the pair of single pipes.

For the service pipes, we compared two types of single pipes with two types of circular twin pipes and a triple pipe. We took a pair of ø 25/77 mm pipes as the reference case. Although this pipe is commonly used by the district heating companies it can be argued that its capacity is too big for modern houses. We found that the triple pipe reduces the heat loss by 45% compared with the reference case and by 24 % compared with a circular twin pipe. The reduction in investment index is 21 %.

When the heat loss coefficients have been determined the heat losses can be calculated for different temperature sets. For instance the amount of heat going from the forward line to the return line can easily be calculated. For the medium sized distribution pipe of ø89 mm and with 80˚C forward temperature, we found that only when the return temperature is below 30 ºC will the return pipe receive more heat from the forward line than it looses to the surroundings.

For the service pipe of 20 mm with 70˚C forward temperature, we found that only when the return temperature is below 23 ºC will the return pipe receive more heat from the forward line than it looses to the surroundings.

In case of 20 mm service pipes, further savings in heat losses of approximately 10% can be achieved by replacing the twin media pipes in the insulation, so the forward pipe approximately touches the centre of the casing pipe.

There are hardly any direct savings by utilising media pipes of dissimilar dimensions of media pipes in case of small dimensions. However including the effect saved temperature loss in the forward pipe of service pipes, then they become significant. Using pipes of dissimilar dimensions together with pipes of even dimensions to obtain more flexible capacity adjusting will also lead to savings.

Acknowledgement

This work has been partially supported by the Energy Research Programme, Danish Energy Authority, grant no. 1373/01-0035. Niels Kristian Vejen, Technical University of Denmark, carried out the finite element model simulations. The support and help is very much appreciated.

List of symbols

A	Area of asphalt, m^2
C	Cost of straight pipelines, £
D	Diameter, m
E	Excavation cost, £
F	Cost factor of components
G	Network structure index
I	Investment, £
M	Volume of materials, m^3
p_{ji}	System constant, W/(m·K)

P	Material price factor (incl. work)
q	Heat loss (Linear density of heat flow rate), W/m
T	Temperature, K or ºC
U	Heat loss coefficient (Linear thermal transmittance), W/(m·K)
V	Volume of gravel, m^3
x	Distance, m
ø	Exterior pipe diameter, mm

GREEK LETTERS

λ	Thermal conductivity, W/(m·K)

Subscripts

a	Asphalt
c	Casing
g	Ground or gravel
i, j, n	Number
i	Exterior surface of the insulation
p	Exterior surface of the steel pipe
r	Return pipe
f	Forward pipe
tot	Total

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