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Energy analysis between traditional hot water circulation system and an innovative pipe-in-pipe system

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Preface

I would like to take this opportunity to thank, first of all, both the University of Gävle in general for giving me the opportunity to do this master's degree and for welcoming me from the very beginning as a lifelong student, and in particular the professors Magnus Mattsson and Roland Forsberg for making the completion of this thesis easier for me with their knowledge and patience.

I would also like to thank both my family, especially my parents, and my closest friends for supporting me in my decision to be absent from their lives for a whole year, many kilometers away but never leaving my side at any time. And, of course, also to my Erasmus friends, because thanks to them this stay has become one of the best experiences of my life that I will never forget.

Abstract

We are at a time when energy efficiency and the reduction in the use of non-renewable energy is an important objective in all aspects and will continue to be so, therefore it is necessary to try to reduce energy and heat losses in the systems used in homes and, in particular, in the domestic hot water (DHW) system. This study aims to find out the advantages and disadvantages of an innovative pipe-in-pipe (PIP) system for DHW circulation with respect to the conventional system of two separate pipes. Previous studies have shown that DHW circulation is indeed an important point of energy losses in the home and that it is possible to reduce these losses by using the innovative system under study. The properties and coefficients defining the heat transfer system have been obtained for both the traditional and innovative systems by using empirical equations and iterative processes, indicating a 32% reduction in heat losses in favour of the pipe-in-pipe system. However, this result has been obtained in a kind of case study, using some simplifying assumptions, needed to accomplish to work within limited time. So the result could vary if a somewhat different system is studied, which is why it is necessary to carry out further studies and research on this subject in order optimize DHW systems in buildings.

Keywords: hot water circulation, pipe-in-pipe, energy saving, buildings, heat losses, warm water.

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1 Introduction

1.1 Background

Hot water circulation is the system of pump, pipes and fittings by which we can obtain water at any water outlet in our homes at the right temperature to carry out the necessary activities such as cooking, showering, washing clothes, etc.

When people talk about reducing the energy used in a house or about zero-energy buildings (ZEB), they always tend to think mainly about insulating the outside surface of the building or using more efficient appliances, but the reality is that in many countries the domestic hot water circulation system is the one with the second highest energy consumption in buildings, after space heating. This is shown in (Pérez-Lombard et al.,2008), as domestic hot water production accounts for 14% of total energy consumption in the European Union. Therefore, more research should be done on improving energy efficiency or finding alternative systems to move hot water in buildings up to the point of use.

The interest of this study lies in the possibility of finding an innovative system to reduce energy use but obtaining the same final objective as the traditional system, which is to be able to use hot water, obviously, at a temperature that does not allow the appearance of legionella. In order to do this, it will be necessary to know the difference in heat losses between the two options to decide which is more favourable in relation to the proposed objective. In addition, better use of energy is likely to have the effect of having to produce less energy (probably obtained mostly from non-renewable means) due to lower energy losses with a consequent benefit for the environment.

1.2 Aims

The papers consulted for the literature review and the further work involved in the thesis itself try to answer a research question, which could be posed as to what extent an improvement in heat loss is obtained between a conventional DHW distribution system and an innovative pipe-in-pipe system?

The main objective of the thesis is to find out what advantages or disadvantages the pipe-in-pipe system for DHW has in comparison with the traditional system of using two separate pipes for the distribution and recirculation of DHW, as well as to carry out the necessary calculations to reach these conclusions, such as, for example, which system has higher heat losses.

A limitation present in the study has been the time limit since it has not been possible to include in the study an economic analysis that complements the study to know if it is effectively feasible to change from one system to another both technically and economically.

1.3 Approach

This pipe-in-pipe or concentric pipes innovative system consists of changing from having two separate pipes for supply and recirculation to two concentric pipes in such a way that the supply water flows through the outer pipe and when it reaches the end it flows back through the inner pipe, as indicated in the Figure 1 below.

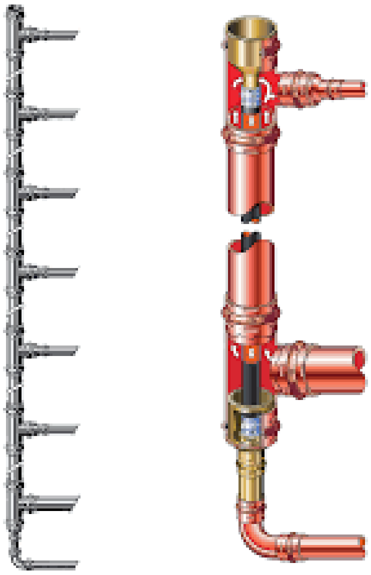

Figure 1. Innovative pipe-in-pipe system. (Viega, 2014)

The study has been performed by using equations in the field of heat transfer, as well as iterative processes to obtain the needed properties, constants and values to obtain the heat losses in both systems.

2 Literature review

For the search of existing literature related to the topic of the thesis, the database *"Discovery"* of the University of Gävle has been used.

As mentioned in the previous section, the provision of hot water in drinking installations is an important point of energy loss, as in residential buildings these losses can correspond to approximately 65% of the energy consumption (Bøhm & Danig, 2004) (Cholewa et al., 2019). This seems to be a relevant subject of study but although there are many articles related to domestic hot water, the particular fact of taking into account the energy losses in the circulation of this water is rare and even totally neglected in some cases (Bøhm, 2013). Some studies where this part of the energy losses have not been eliminated are discussed at (Hamburg et al., 2021) where it is observed that, indeed, the circulation losses are important. (Bøhm & Danig, 2004) states that the losses in the domestic hot water system of the building under his study were between 23 and 70%. (Horváth et al., 2015) gives as a result of his respective study that water distribution and circulation losses are between 5.7 and 9.9 kWh/(m^2·a). Another report that is in agreement with the results expressed before is that of (Marszal-Pomianowska et al., 2019) where the circulation accounts for 16 to 50% of the heat consumption of domestic hot water. From these reports it can be concluded that the percentage of DHW losses is higher in buildings with low total DHW consumption. It is also interesting to note that when the DHW consumption is low, such as in single-family houses, the circulation losses are of the same order as in a larger building. It can also be interpreted that knowing the amount of energy that is continuously lost in a fundamental part of buildings, this aspect should be taken more into account in the design and construction of new buildings.

In order to try to reduce DHW consumption, several studies have been carried out using different techniques. Some of these are the use of an electrical tracing system, combining pipes for space heating and DHW in the same insulation and, finally, using a coaxial pipe system for the DHW circuit.

(Arabkoohsar et al., 2020) analyses another way of reducing heat loss, which is to combine more than one pipe in the same thermal insulation. Specifically, it compares the use of 2 pipes in the same insulation with the use of 3 pipes, the space heating and the DHW pipes. The results of this study show that it does not matter which lay-out for the 3 pipes is used, it will always be more favourable in terms of energy losses that than the use of only 2 pipes.

This could be beneficial in the design of new buildings as switching from the traditional system to the use of pipes with the same insulation can be very costly for an existing building.

(Yang et al., 2016a) in their study try to compare the costs and energy consumption in DHW using the electric heat tracing method with the coaxial pipe system in the same building. The electric heat tracing consists of using a cable around the pipe whose function is to heat, using control methods, the water that passes through it to the necessary temperature so that legionella does not proliferate, in this way it is not necessary to install a circulation pipe. Their results show that with the electrical tracing it is possible to save between 34 and 67% of the losses. However, due to the heat required to heat the water, the overall consumption is higher than for the pipe-in-pipe system.

It seems that the option of electric heat tracing is favourable in terms of price for the consumer due to the savings of having to heat the water with district heating to a lower temperature. However, if we focus on the main objective of using less energy, it is the coaxial pipe system that benefits. In addition, a study should be made of how non-constant heating with electricity over long periods of time can affect the pipes in the long term.

(Yang et al., 2016b) use the in-liner circulation system in their study to analyse how much energy is saved by using a decentralised substation system for DHW in the dwellings of a building instead of the conventional centralised system. When comparing the results of the scenario with decentralisation without the in-liner method with the scenario where the pipe-in-pipe system is added, a reduction of 12% is obtained. From these reports we can think that what the manufacturers of the in-liner system say about their system may be true.

These manufacturers are Viega and Geberit. Viega states that 20-30% less losses can be achieved in DHW distribution (Viega, 2014), Geberit is in the same line and also states a saving of up to 30% (Geberit, n.d.). However, as there is not much literature on this system, these loss reduction data should be taken with caution.

A major health problem in the domestic hot water system is the occurrence of micro-organisms and in particular the occurrence of Legionella. For this reason, there are numerous studies that analyse the temperature range in which the proliferation of colonies of this microorganism is more likely, the speed at which they proliferate and whether the stagnation of water is an important factor in their appearance. This is commented in (van der Kooij et al., 2005) where it is said that temperatures between 25 and 45 degrees as well as long residence times increase the proliferation of legionella. These are clearly parameters to avoid in a drinking water system.

After the literature review, knowledge has been obtained about the importance of improving the energy efficiency of the DHW system in buildings, as well as the importance of the temperatures involved in the system in order to prevent legionella and health problems for people, and some of the techniques studied and used for this purpose, which will be used to obtain and discuss the results in the thesis.

3 Methods

In order to achieve this, the research method used will be that of an analytical case study because we observe how the two DHW systems behave and what results are obtained under specific but reasonable conditions.

And once the study has been carried out and described in the thesis, it will be perfectly reproducible and repeatable by another researcher with no more effort than using the same data and model used to carry out this thesis. By using the same initial data, the same results would be obtained.

The research is mainly based on heat transfer in pipes designed for the transport of domestic hot water, so first of all it is necessary to know what types of heat transfer can occur in this type of system.

The two methods that have the greatest effect on heat transfer are conduction through the materials that the pipes are made from and convection, both forced and natural, due to the water that goes through the pipe and the external environment, respectively. Radiation is also going to be taken into account even though the temperature of the materials can not be too high to avoid health problems due to burns (Energi Företagen, 2016).

Heat transfer by conduction is a process based on direct contact between bodies, with no exchange of matter, as heat flows from a higher temperature body to a lower temperature body in contact with the first. It also happens in the same body if different parts of it are at different temperatures. The physical property of materials that determines their ability to conduct heat is thermal conductivity, k.

The heat flow by conduction is defined by Fourier's law. In our case, the systems are cylindrical, so applying cylindrical coordinates to Fourier's law gives the following expression:

$$q_{cond} = \frac{2 * \pi * k * L * (T_i - T_o)}{\ln {}^{r_o}/_{r_i}} \tag{1}$$

Convection is the transport of heat by the movement of a fluid and the temperature gradient depends on the rate at which the fluid carries the heat away.

The effect of convection is expressed by Newton's cooling law:

$$q_{conv} = h * A * (T_w - T_\infty) \tag{2}$$

Where h is the convection heat-transfer coefficient, A the area of contact with the fluid and $(T_w\text{-}T_\infty)$ the overall temperature difference.

There are two types of convection, natural or free and forced. The first occurs by the simple fact that when the fluid comes into contact with a surface with a different temperature, it heats up or cools down and, therefore, its density varies, creating density gradients that cause the fluid to move. The second type is caused by the action of an external agent such as a fan moving air or, in the case of this study, the flow of a liquid through a duct. In addition, the convection heat-transfer coefficient, which can be obtained analytically if the system is simple or experimentally, depends on the type of convection experienced.

Radiation is a method of heat transfer which, unlike conduction or convection, does not need a material medium to occur as it can exist even in a vacuum. This type of radiation, which does not appear in the study, is called electromagnetic radiation. The type of radiation that is present in this system is due to the difference in temperature between two bodies and is called thermal radiation.

The problem of heat transfer in a physical system can be modelled using the electrical analogy to move on to resistances, heat flow (intensity in the analogy) and temperature differences (voltage difference in the analogy). Thus, in order to know the heat flow in the system, i.e. the heat losses, it is necessary to know both the resistances and the temperature difference.

The traditional domestic hot water system consists of an insulated pipe for supply and another, also insulated and of smaller diameter, for recirculation. The following figure shows the cross-section of these pipes as well as the thermal resistances present in their corresponding electrical analogy.

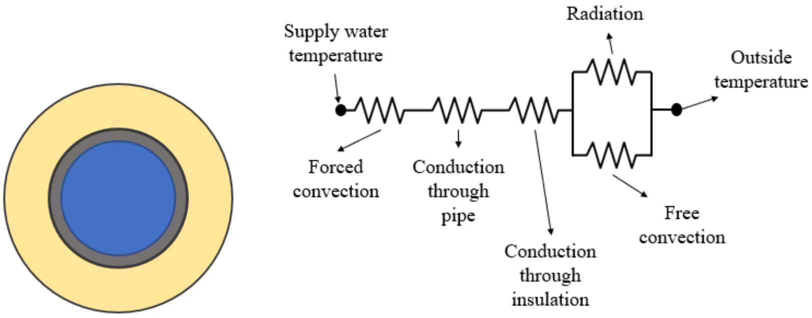

FIGURE 2. CROSS SECTION AND ELECTRICAL ANALOGY OF A HOT WATER PIPE IN THE TRADITIONAL SYSTEM.

The thermal resistances that oppose high heat flow to the outside are due to forced convection inside the duct, conduction through the pipe and insulation and free convection outside.

The temperature of the hot water will be higher than the temperature outside so, in this case, the heat flow will be from the inside of the pipe to the outside. In an ideal system, these losses should be zero, as all losses involve both loss of money and damage to the environment, but creating an ideal system is impossible, so the optimum would be for them to be as small as possible.

The innovative pipe-in-pipe system also consists of two pipes (one for supply and one for recirculation) but with the particularity that they are not separated. The recirculation pipe is located inside the supply pipe.

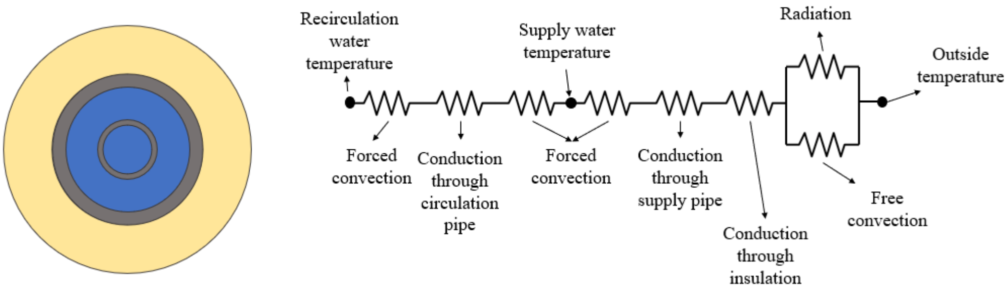

FIGURE 3. CROSS SECTION AND ELECTRICAL ANALOGY OF A HOT WATER PIPE IN THE PIPE-IN-PIPE SYSTEM.

As it has been mentioned, the supply is made through the external pipe and it is there where the highest temperature will be found, so it can be observed that now there will not be only one heat flow but two. One towards the outside of the system and the other towards the inside, towards the recirculation water.

The heat flow towards the outside will be subject to the same thermal resistances as in the previous case but the heat flow towards the recirculation will be affected by the forced convection on the outside wall of the inner pipe, a conduction through this pipe and, again, another forced convection inside the pipe of smaller diameter.

We will now explain and detail the method and procedure used to calculate both the heat losses and the temperatures present in the traditional system and, subsequently, the same will be done for the innovative system. It is necessary to clarify that the procedures will be detailed for both systems because although the purpose is the same, the way of carrying it out presents differences.

The first step to obtain the heat losses in both systems is to know the values of the thermal resistances that affect each of them.

The resistance due to conduction through a circular surface is as follows:

$$R_{cond} = \frac{\ln {}^{r_o}\!/_{r_i}}{2 * k * \pi * L} \tag{3}$$

The thermal conductivity values depend on the materials used.

The system can be assumed to be infinite since the length of the pipes is much larger than their diameter so the heat transfer coefficient due to radiation can be expressed using the following formula:

$$h_r = \epsilon * \sigma * (T_1^2 + T_2^2) * (T_1 + T_2) \tag{4}$$

Where ϵ refers to the emissivity of the external surface of the pipe, σ is the Stefan-Boltzmann constant with a value of $5.669 * 10^{-8}\ {}^{W}\!/_{m^2 * K^4}$ and T_1 and T_2 are the temperatures of the pipe surface and the external environment, respectively.

In contrast to conduction, convection does not depend on the material used but on the properties of the fluid that causes it, whether it is the fluid surrounding the system or the fluid circulating inside the system. The convection thermal resistance is:

$$R_{conv} = \frac{1}{h * A} \tag{5}$$

Where A is the area in contact with the fluid causing convection.

In order to calculate the convection heat transfer coefficient, it is necessary to know whether the fluid causing the convection is in laminar or turbulent regime, since the empirical relations to be used depend on this. This is done by calculating the Reynolds number, although other dimensionless numbers such as the Nusselt, Prandtl or Grashof numbers must also be taken into account for the calculation of the coefficient h.

TABLE 1. DIMENSIONLESS NUMBERS.

Reynolds number	$Re = \frac{\rho * u * x}{\mu}$

Nusselt number	$Nu = \frac{h * x}{k}$
Prandtl number	$Pr = \frac{c_p * \mu}{k}$
Grashof number	$Gr = \frac{g * \beta * (T_w - T_\infty) * x^3}{\upsilon^2}$

Being ρ the density of the fluid, u the mean velocity, x the characteristic length, μ the dynamic viscosity, c_p the specific heat, k the thermal conductivity and β the coefficient of thermal expansion.

After knowing the regime of the water inside the pipes and the air outside the pipes, the empirical relations are used to calculate the convective heat transfer coefficient.

The most famous equation in the calculation of forced convection is the one recommended by Dittus and Boelter (Winterton, 1998):

$$Nu_d = 0{,}023 * Re_d^{0{,}8} * Pr^n \tag{6}$$

The value of n depends on whether the fluid is heated (n=0,4) or cooled (n=0,3). Furthermore, the values for the Prandtl number must be between 0.6 and 100 and for the Reynolds number between 2 500 and 1.25x10^5.

However, (Gnielinski, 1976) states that better results can be achieved if the Prandtl number is between 1.5 and 500 and the Reynolds number between 3 000 and 10^6, using the following formula:

$$Nu_d = 0.012 * \left(Re_d^{0{,}8} - 280\right) * \mathrm{Pr}^{0{,}4} \tag{7}$$

The equations to be used in the case of free convection depend not only on the regime of the air near the pipe but also on the position of the pipe, i.e. whether it is vertical or horizontal, since convection is associated with the boundary layer of the fluid.

In this case, the laminar or turbulent regime is not associated with the Reynolds number but with the product of the Grashof number and the Prandtl number. If this product is between 10^4 and 10^9, the regime is laminar, while if it is higher, it becomes turbulent.

The equations for vertical cylinders in laminar and turbulent regimes, respectively, are as follows:

$$h = 1.42 * \left(\frac{\Delta T}{L}\right)^{0{,}25} \tag{8}$$

$$h = 1.31 * \Delta T^{0{,}33} \tag{9}$$

Whereas for horizontal cylinders:

$$h = 1.32 * \left(\frac{\Delta T}{d}\right)^{0{,}25} \tag{10}$$

$$h = 1.24 * \Delta T^{0,33} \tag{11}$$

Where ΔT corresponds to the temperature difference between the cylinder wall and the surroundings.

For forced convection there is no impediment and it can be carried out directly. In the case of free convection, as can be seen in the equations, it is necessary to know the temperature of the wall, i.e. the outer surface of the insulation, which is not known a priori. For this reason, the calculation of the free convection coefficient requires an iterative process starting with an assumption of the temperature of that surface. This process aims to obtain the temperature outside the pipe by iterating until the temperature is similar to that of the previous iteration with an acceptable error.

It is necessary to assume the temperature outside the pipe since the properties of the outside air must be evaluated at an average temperature between the pipe temperature and the outside temperature, called film temperature. Once the properties of the air at that temperature have been obtained, the Grashof and Prandtl numbers are calculated to establish which regime the air is in and to apply the equations related to the laminar or turbulent regime and being able to obtain the free convection coefficient. The next step in the process is to balance the heat flow from the inside to the outside in order to clear the temperature outside the insulation and compare it with the assumed temperature. The balance deduced from the electrical analogy presented in Figure 2 is as follows:

$$\frac{T_{water} - T_{insul}}{R_{forced} + R_{cond_{pipe}} + R_{cond_{insul}}} = \frac{T_{insul} - T_{outside}}{\frac{1}{\left(h_{free} + h_{rad}\right) * A_o}} \tag{12}$$

If the error in assuming the insulation temperature is too high, the same process is repeated, this time using this temperature to calculate the film temperature in the air properties calculation until the error is reasonable.

Once all the values of resistances and temperatures are known, it is possible to calculate the heat flow to the outside by performing the complete balance. By multiplying this heat flow by the length of the pipe, the total heat loss is known and it is possible to obtain the temperature at the end of the pipe using the following equation.

$$q = \dot{m} * c_p * (T_1 - T_2) \tag{13}$$

By performing exactly the same procedure, it is possible to calculate the losses in the recirculation part, which will be different because the diameter of the pipe in that area is smaller, changing the values of all the properties. The sum of heat losses and temperature drops from the supply and recirculation part will give the total losses and the total temperature drop of the system that the district heating will then have to supply.

The procedure used in the calculation of the innovative pipe-in-pipe system is explained below. It has been previously mentioned that in this system there are two different heat flows and, again, only the inlet temperature of the hot water is known as it is defined by the district heating system. In the case where there is only heat flow to the recirculating water, the system could be approximated to a counter-flow double pipe heat exchanger without heat losses, the appropriate equations would be applied and the necessary results would be obtained, but in this case there are losses modelled as heat flow to the outside of the system.

Firstly, it will be assumed that the only heat flow is to the recirculation, calculating it using the NTU method, (Holman, 2010), for heat exchangers and thus having both heat flow and temperatures at the end and start of the pipe as a starting point for the iterative process. Subsequently, the heat flow to the outside will be calculated in the same way as in the traditional system, with another iterative process. Both heat flows will be added together to calculate the temperature loss in the supply water and compare it with the temperatures calculated in the first assumption. If the difference is too big, the process continues.

The overall heat transfer coefficient multiplied by the heat transfer area for the assumed heat exchanger between the supply water and the recirculating water is shown in the following equation:

$$UA = \frac{1}{\frac{1}{h_{forced_{recir}} * A_{recir}} + \frac{\ln {}^{r_s}/_{r_r}}{2 * \pi * k * L} + \frac{1}{h_{forced_{supply}} * A_{supply}}} \tag{14}$$

A_{recir} being the area of contact between the recirculation water and the recirculation pipe, r_s and r_r being the outer and inner radii of the recirculation pipe, respectively, and A_{supply} being the area of contact of the supply water, again, with the recirculation pipe. Both convection heat transfer coefficients are obtained from the Nusselt number equation obtained from (7), taking into account that the characteristic dimension for forced convection in the recirculation pipe is the internal diameter itself, while for forced convection in the supply pipe it is the hydraulic diameter.

The next step in the NTU-method is to calculate the capacity rates of both fluids, which in this case will be equal since the fluid is the same. These capacities are defined as the multiplication between the mass flow rate and the specific heat of the fluid. The number of transfer units (NTU) is obtained by dividing the UA factor by the fluid capacity rate and the effectiveness (ε) of the heat exchanger can be obtained using graphs.

Using the effectiveness, it is possible to obtain the temperature at the end of the supply pipe which, when connected, is the same as the temperature at the beginning of the recirculation. The effectiveness of a counter-flow heat exchanger is defined as follows:

$$\varepsilon = \frac{T_{h_1} - T_{h_2}}{T_{h_1} - T_{c_2}} \tag{15}$$

Where the sub-indices h and c indicate whether the fluid is the hot or the cold one and sub-indices 1 and 2 indicate whether it is at the entry or exit point of the heat exchanger, respectively.

Using the balance of (13), the heat flux to the interior can be obtained, to which the heat flux to the exterior must still be added. This heat flow is obtained in the same theoretical way as in the traditional system as it is affected by the same thermal resistances.

Once both heat flows have been added together, the same balance from (13) is used again to obtain the new temperature at which the supply water would reach just before entering recirculation.

The last step before completing the iteration is to perform the balance to the recirculating water using the temperature obtained in the paragraph above and the heat flux to the recirculating water that was previously obtained at the beginning of the iterative process. This heat flux will change in future iterations as new temperatures are obtained, the properties must be re-evaluated and the UA factor re-calculated.

The following figure shows a scheme representing the procedure to be followed in the iterative process previously explained for obtaining the temperatures and heat fluxes in the pipe-in-pipe system:

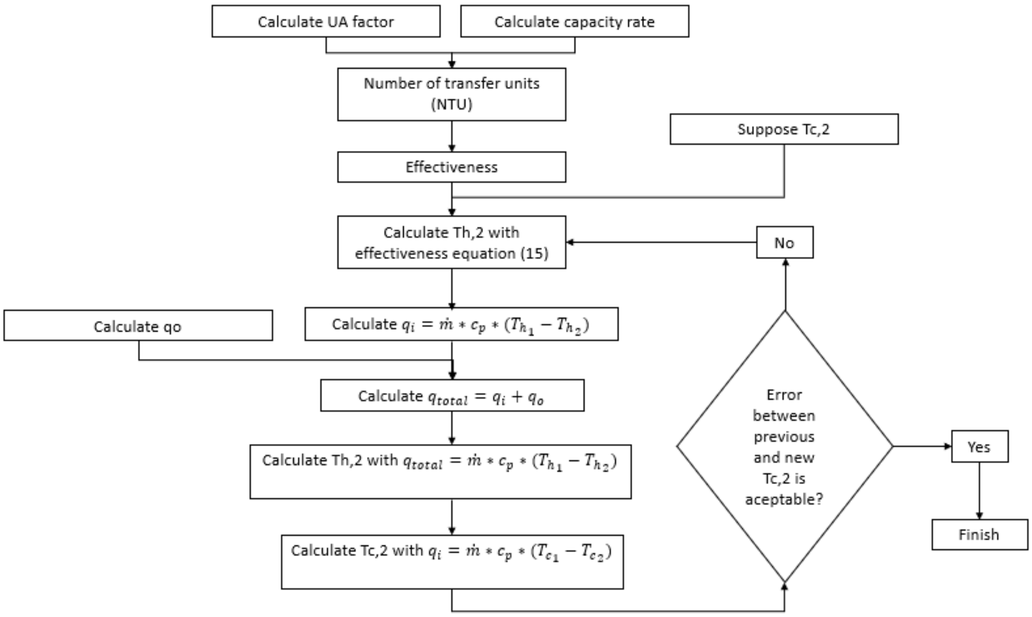

FIGURE 4. ITERATIVE PROCESS IN THE INNOVATIVE SYSTEM.

Once the general relations and how to solve the problem have been discussed, it is necessary to establish the particular concepts for each way of carrying out the domestic hot water supply.

These particular concepts are the initial data available at the beginning of the study and are composed of the inlet temperature of the hot water, geometrical data of the system, materials used both in the pipes themselves and in the insulation surrounding them and the flow rate of water entering the system. It is necessary to clarify that these data and no others have been chosen thanks to the experience of Roland Forsberg who is an experienced HVAC consultant at Sweco.

The following table shows the geometrical data used to solve the problem.

TABLE 2. GEOMETRIC DATA FOR EACH SYSTEM.

	Traditional		**Innovative**	
	Supply	Circulation	Supply	Circulation
Internal Diameter (mm)	35	12	35	10
Pipe Thickness (mm)	1.5	1	1.5	1
Insulation Thickness (mm)	30	30	30	0

Apart from the size of the pipes it is also necessary to establish the length of the pipes in order to calculate the total losses. The total length used is 100 metres of which 50 metres are for supply and 50 metres for recirculation.

It is assumed that a flow rate of 250 l/h, corresponding to a not excessively large building, will flow through these pipes.

The study is being carried out on the assumption that residential buildings are to be supplied with domestic hot water, so the outlet temperature of the district heating station is 55ºC, although if a storage tank is used the temperature should be 60ºC, which coincides with the maximum temperature to avoid scalding (Energi Företagen, 2016). An initial temperature of 60ºC will be used as this way the temperature difference with the outside is higher, which makes it a more unfavourable case as the heat flux will be higher.

The selected materials for the study are the typical used in domestic hot water systems in residential buildings in Sweden. The supply and recirculation pipes in the traditional system are made of copper and the insulation covering them is mineral wool. The materials used in the innovative system vary only in the internal tubing as it is a polybutene hose, as stated by the manufacturer Viega (Viega, 2014). The insulation and the outer tubing are made of the same materials as in the traditional case.

The values for thermal conductivities of each material used in the study are presented in the following table:

TABLE 3. PROPERTIES OF MATERIALS USED IN THE STUDY. (BAI & BAI, 2014; HOLMAN, 2010; ISOVER, 2017)

	Thermal conductivity $(W/_{m * °C})$	Emissivity
Copper	382	
Mineral Wool	0.037	0.94
Polybuten	0.2	

Normally the pipe also has a thin plastic layer around it which most probably also has a high emissivity value as well as the mineral wool insulation layer.

After having commented and detailed the procedure and the equations used in the solution of the problem in order to obtain the heat losses in both systems to be studied, and before presenting and discussing the results in the following section, it is necessary to comment that all calculations of both iterative processes and simple equations have been carried out using Excel.

4 Results and discussion

As was done in the methods section, the results obtained for the traditional system will be discussed first, followed by the results for the pipe-in-pipe system.

The first element to be calculated in the process is the convective heat transfer coefficient for the forced convection inside the pipes.

The values obtained are as follows:

TABLE 4. DATA FOR THE CALCULATION OF THE FORCED CONVECTION COEFFICIENT H IN THE TRADITIONAL SYSTEM.

Forced Convection Heat Transfer Coefficient		
	Supply	Circulation
Re	6 153,07	15 047,33
Pr	3.01	3.08
h(A) ($W\ m^{-2}$ °C^{-1})	690.74	4 127.95
h(B) ($W\ m^{-2}$ °C^{-1})	749.9153	4 315.565
Difference	7.89%	4.35%

It has been mentioned above that two different ratios can be used to calculate the Nusselt number in forced convection. After applying the definition of this dimensionless number, the coefficient h is obtained. h(A) refers to the value obtained by using (7) while h(B) is obtained by using (6).

In addition, the percentage error made when using one equation or the other was wanted to show in the table. It will be observed later on whether this fact has an important relevance that could affect the final results of the study or not. For the rest of the results in the study in which the convection coefficient of heat transfer in forced convection is involved, the value h(A) will be used since, according to (Gnielinski, 1976), better results are obtained by applying this equation, obviously if the conditions for its use are met. These conditions have been discussed in the methods section and, indeed, are met as can be seen in Table 4.

For the calculation of the free convection on the outside of the circulation pipe, an iterative process had to be carried out due to the unknown temperatures as explained in the previous section. The data now presented are those obtained after completion of the iteration process.

TABLE 5. DATA FOR THE CALCULATION OF THE FREE CONVECTION COEFFICIENT H IN THE TRADITIONAL SYSTEM.

Free Convection Heat Transfer Coefficient		
	Supply	Circulation
Pr	0.7096	0.7097
Gr (Vertical)	5.83E+12	4.592E+12
Gr (Horizontal)	3.00E+05	1.19E+05
Gr*Pr (Vertical)	4.14E+12	3.26E+12
Gr*Pr (Horizontal)	2.13E+05	8.45E+04
h (Vertical) ($W\ m^{-2}$ °C^{-1})	1.798	1.658
h (Horizontal) ($W\ m^{-2}$ °C^{-1})	3.031	3.02

In this case rows have been added assuming that the whole system is horizontal or vertical as the equations vary depending on this fact. Observing the values for the vertical system we obtain a turbulent regime since the multiplication between the Grashof number and the Prandtl number is greater than 10^9 so (9) will be used for the calculation of h while the regime for the horizontal system is laminar so (10) will be used for this case.

It might be expected that having the system horizontal or vertical would mean a large change in the values of the heat transfer coefficient, but from the data in Table 5 it can be seen that this is not the case. This is because, as can be seen in the equations used, by obtaining a turbulent regime in the vertical system, the length of the pipes is no longer a factor to be used.

The last heat transfer coefficient to be calculated is the radiation coefficient, the values of which are shown in the following table:

TABLE 6. RADIATION HEAT TRANSFER COEFFICIENT PRESENT IN THE TRADITIONAL SYSTEM.

Radiation Heat Transfer Coefficient ($W * m^{-2} * K^{-1}$)	
Supply	Circulation
5.43	5.42

The same value is obtained for the supply pipe as for the circulation pipe, since the radiation is strongly dependent on the temperature of the external surface and this is practically identical for both pipes.

Once all the parameters defining the thermal resistances have been obtained, the following values are obtained:

TABLE 7. THERMAL RESISTANCES PRESENT IN THE TRADITIONAL SYSTEM.

Thermal resistances (m*ºC/W)		
	Supply	Circulation
Forced Convection	0.01536	0.00643
Conduction_pipe	3.78E-05	6.12E-05
Conduction_insulation	4.4567	7.162
Free Convection 50%V	1.4176	1.8391
Free Convection 20%V	1.23	1.57
Radiation	0.63	0.794

Two different thermal resistances are shown for free convection as one of them has been obtained assuming that 50% of the pipe length is in vertical position while for the second value only 20% of the total length of the system is assumed to be in vertical position. These values are quite similar and, from this, it can be concluded that whether the pipes are in a vertical or horizontal position does not significantly affect the results obtained. As mentioned above, this fact is related to the turbulent regime that appears in vertical pipes due to the detachment of the boundary layer. Another conclusion that can be drawn from this data is which thermal resistance, i.e. which element in the system has the greatest impact on the total heat loss. This highest value for thermal resistance is given for conduction through the thermal insulation, so a variation in its thickness, its use or not or a change of the material used for it can have a big impact on the heat loss obtained. The value obtained for free convection is of the same order of magnitude as for conduction through the insulation and because of that it is also an element that controls the overall heat transfer coefficient, although to a lesser extent. As expected, the conduction resistance through the copper pipe is negligible as it is a conductive material.

Having analysed and obtained all the influential parameters in the traditional domestic hot water system, the results of heat losses are shown in the following table:

TABLE 8. HEAT LOSSES IN THE TRADITIONAL SYSTEM.

	Heat Losses (W/m)		**Total Heat Losses** (W)		
	Supply	Circulation	Supply	Circulation	Total
50% Vertical	8.15	4.99	407.47	249.72	657.19
20% Vertical	8.18	4.99	409.11	249.72	658.83

Two different results have been obtained, one for 50% vertical pipe and one for only 20%, in order to compare both results and to see if this is an important factor in the losses.

The main conclusions drawn for the traditional system from the analysis of these results are that, as could already be anticipated from the free convection heat transfer coefficient, the fact that less of the pipe is in a vertical position is not a significant factor in the total heat losses as it only reduces the total heat losses by a total of 1.7W. Another more important conclusion is the fact that the recirculation of water leads to lower heat losses than the water supply itself. The reason for this can be seen in Table 7 as it is clearly observable that the dominant resistance in the system has a higher value for recirculation than for supply due to the smaller pipe diameter and, therefore, higher insulation ratio as the thickness used for both pipes is the same. The use of the same thickness despite having a smaller diameter may be due to lower costs and greater ease of assembly if a very high number of pipes are to be produced, or because the smaller diameter means that the fluid velocity will be greater and, therefore, greater losses can be expected if less insulation is used or not used at all.

The temperature drop is an important factor to take into account since, as stated in the regulations, the temperature at no point in the system can be lower than 50℃ to avoid the spread of legionella (BBR, 2018).

TABLE 9. TEMPERATURE DROP IN THE TRADITIONAL SYSTEM.

Temperature drop (℃)		
Supply	Circulation	Total
1.43	0.91	2.33

Using (13), firstly for the supply pipe and then for the recirculation one, the values in the table above are obtained, where it can be seen that the temperature loss is not large enough to obtain temperatures below 50℃.

The results obtained for the concentric piping system will now be discussed.

For this system, the forced convection heat transfer coefficient are as follows:

TABLE 10. DATA FOR THE CALCULATION OF THE FORCED CONVECTION COEFFICIENT H IN THE PIPE-IN-PIPE SYSTEM.

	Forced Convection Heat Transfer Coefficient	
	Supply	Circulation
Re	3 808.81	17 671.86
Pr	3.12	3.16
h(A)	548.57	5 789.43
h(B)	670.983	5 931.013
Difference	18.24%	2.39%

Again, the coefficients obtained with both equations are presented, h(A) for (7) and h(B) for (6). It can be seen that in the case of the supply pipe the difference between both results is large and this may be due to the fact that if we look at the Reynolds number, it is quite close to the lower limit for which (7) can be used, so the error may come from the fact that it is not the most optimal area for the application of the equation. However, in the same way as for the traditional system, the result obtained with (7) has been used for the rest of the subsequent calculations.

The values obtained for free convection after the same iterative process as in the traditional system are shown in the table below:

TABLE 11. DATA FOR THE CALCULATION OF THE FREE CONVECTION COEFFICIENT H AND RADIATION IN THE PIPE-IN-PIPE SYSTEM.

Free Convection Heat Transfer Coefficient	
Pr	0.709
Gr (Vertical)	5.948E+12
Gr (Horizontal)	6.58E+02
Gr*Pr (Vertical)	4.22E+12
Gr*Pr (Horizontal	4.67E+02
h (Vertical)	1.82
h (Horizontal) ($W * m^{-2} * °C^{-1}$)	5.104
h (Radiation) ($W * m^{-2} * °C^{-1}$)	5.436

In this case only the supply pipe is subjected to free convection as the recirculation pipe is inside. It can be seen that the change in the position of the pipe in this case is somewhat more noticeable, although it still does not have so much influence. In addition, the value of the coefficient related to radiative heat transfer has been added to the table.

TABLE 12. THERMAL RESISTANCES PRESENT IN THE PIPE-IN-PIPE SYSTEM.

Thermal resistances (m*ºC/W)	
Forced Convection Inside Inner Pipe	0.0055
Conduction Inner Pipe	0.145
Forced Convection in the Outside Wall of the Inner Pipe	0.0483
Forced Convection in the Inside Wall of the Outer Pipe	0.0166
Conduction Outer Pipe	3.26E-05
Conduction Insulation	4.075

Free Convection 50% Vertical	0.938
Free Convection 20% Vertical	0.73
Radiation	0.598

As was the case in the traditional system, the resistance due to thermal insulation is also predominant in the pipe-in-pipe system. It should be noted that the thermal resistance due to the conduction through the recirculation pipe is not copper but polybutene, which has a much lower thermal conduction than copper. In fact, it is the predominant resistance in the heat flow subsystem to the return water over the forced convection due to both water flows.

Using all the values obtained and performing the iterative process explained in the methods section, it is possible to know the heat losses of the supply water to the outside and also to the inside as the recirculation water is at a lower temperature.

TABLE 13. HEAT LOSSES IN THE PIPE-IN-PIPE SYSTEM.

	Heat Losses (W/m)		**Total Heat Losses** (W)	
	Q_outside	Q_inside	Q_outside	Q_inside
50% Vertical	8.98	4.11	448.75	205.45
20% Horizontal	9.05	4.11	452.45	205.45

It is clearly obvious that again the position of the pipes has a negligible effect on the heat losses obtained. In fact, for recirculation, this effect is directly zero, since the only thermal resistance affected by the position of the system is the free convection resistance, and precisely this does not affect the circulation because it is inside the supply pipe.

The temperature drop corresponding to the clear losses obtained is as follows:

TABLE 14. TEMPERATURE DROP IN THE PIPE-IN-PIPE SYSTEM.

Temperature drop (℃)		
Supply	Circulation	Total
1.59	-0.72	0.866

The appearance of a negative sign for the temperature variation in the recirculation is due to the fact that in this pipe section the temperature increases due to the clear flow inwards from the supply water. Therefore, the point of lowest temperature in the innovative system is exactly where the water passes from the supply pipe to the recirculation pipe, whereas in the traditional system this point was at the end of the system, i.e. at the end of the recirculation.

A comparison between the variation of the water temperature along the pipe in both systems can be seen in the following figure:

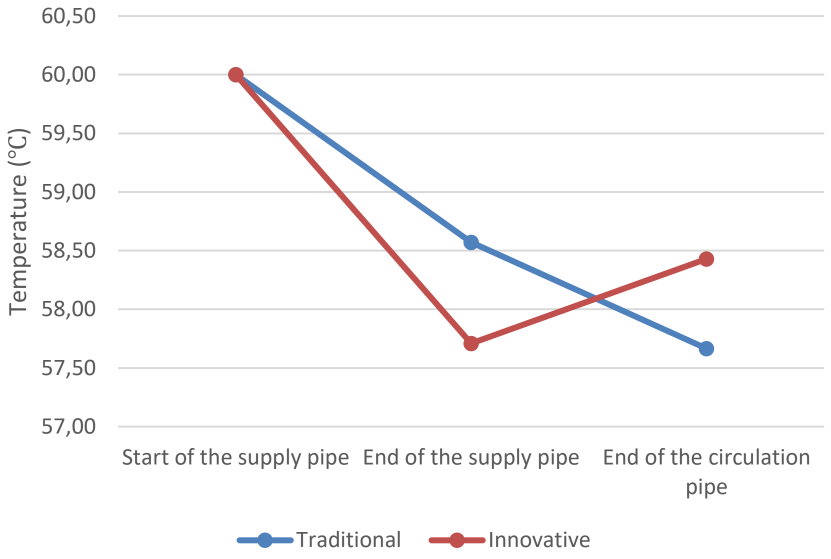

FIGURE 5. WATER TEMPERATURE VARIATION IN BOTH SYSTEMS.

Furthermore, this has another consequence which is that the only heat flow that can be defined as heat loss is the heat flow to the environment as the heat used in raising the temperature of the recirculating water is heat that will not need to be supplied from the district heating substation creating an energy saving at that point. This can be represented as in the figure below:

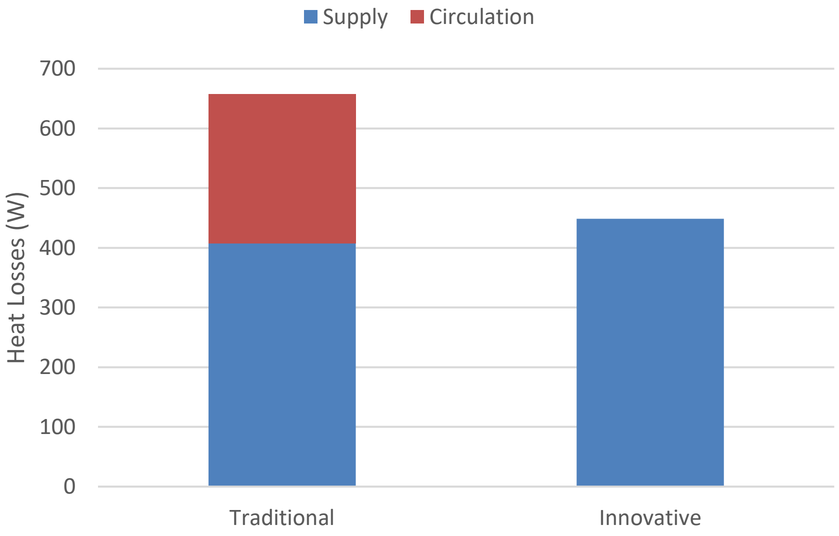

FIGURE 6. HEAT LOSSES COMPARISON BETWEEN BOTH SYSTEMS.

The figure shows graphically how only for the supply side of the innovative system there are somewhat higher losses due to the fact that there is not only heat exchange to the outside but also to the inside. If we look at the supply system, the heat flow towards the interior of the pipe would have to be introduced as heat losses, but when making a general analysis of the complete supply + recirculation system, this heat flow is not really defined as losses, as it is possible to take advantage of this increase in temperature later.

The traditional system has losses of 657.17 W, while for the PIP system this value is 448.74 W. This corresponds to a reduction of 31.7%.

It can be said that the results obtained after carrying out the study following the described method and after analysing the previous literature are favourable for the innovative system. That manufacturers report reduction of losses up to 30% (Geberit, n.d.; Viega, 2014), i.e. principally the same as has been obtained in this study.

After knowing the results, the uncertainties of the study due to the use of assumptions should be expressed. The result with the greatest uncertainty would be the temperature that can be obtained at the taps in the different dwellings, and especially at the one furthest from the starting point, as this is the one that will suffer the greatest drop in temperature. This uncertainty is mainly due to the fact that the study has been carried out taking into account that at all points there is the same water flow as at the start, which in reality is not true, as different dwellings can use hot water systems at the same time. This decrease in flow rate along the supply pipe would cause the temperature drop to be higher than calculated due to the lower velocity of the water resulting in higher heat transfer. This would, of course, affect the pipe-in-pipe system to a greater extent.

Another problem can occur when deciding to change from the traditional system to the PIP system, as the minimum internal diameter of the external pipe has to be 28 mm, so even if such a large diameter is not required, it would still have to be installed and, therefore, the system would be oversized. In addition, for the dimensioning it must be taken into account that 12 mm of diameter is lost inside the external pipe due to the recirculation hose, so that, probably in a traditional system the necessary diameter of the pipe is 28 mm but when installing the PIP system this necessary diameter is bigger so that the water flows more or less at the same speed as in the traditional system. This data regarding installation and dimensioning has been provided by Jan Matuszczyk, Regional Manager West SE at Viega Sweden.

5 Conclusions

5.1 Study results

The aim of this study was to analyse and corroborate if it is possible to reduce the heat losses in the domestic hot water system in residential buildings by changing the traditional system in which two separate pipes are used for the distribution and recirculation of water to two concentric pipes.

After making a number of assumptions in the system such as using the total pipe length of the system and not the actual pipe layout of a specific building, a 31.7% reduction in heat losses has been obtained. Therefore, it can be concluded that in terms of heat losses, this new system has advantages over the traditional system that can lead to energy savings and an improvement in the environment. This is precisely the main advantage of the system, while the main disadvantage is the fact that it should be necessary to carry out an exhaustive analysis using flow rates and times of coincidence in the use of hot water to ensure that with the PIP system a temperature of less than 50℃ is not obtained in the taps of the dwellings furthest away from the district heating heat exchanger, since with this new system it is at the furthest point where the lowest temperature is obtained.

5.2 Outlook

The fact that assumptions have been made leaves the door open for future studies to be carried out. An improved method for the development of this study could be achieved by using actual data on a particular building and system so that no assumptions are made about existing water flow rates, lengths or geometrical data of the system.

In addition, the fact that this system has only recently emerged makes it more attractive for installation in new buildings as they would not have to change most of the piping system in the building as would be the case in an existing building if they wanted to use this innovative system. Therefore, a new research question could arise for existing buildings and that is, would it be economically viable to switch from one system to another? For this purpose, an economic analysis of the payback time for changing the traditional system and installing the PIP system could be carried out.

5.3 Perspectives

In a wide future perspective, this study can give society gains in relation to the possible lower use of fossil fuels because less energy will be needed in the DHW system as energy losses are reduced.

Therefore, if many if not all buildings use this system and save a small amount of energy each in the form of reduced heat losses, the domestic hot water system will be more sustainable by using less energy to heat the water, thus creating less negative effects on the environment.

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