Simulation of moisture alarm for district heating networks

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Abstract

This master thesis hopes to be a first approach in the study of the moisture control of the district heating networks. Nowadays the moisture control is based on the resistance value analysis and the time-domain reflectometer usage. These two technic has been proved to be an effective combination in order to detect and localize leakages in the networks. Despite this fact, there is not a wide knowledge about the actual behaviour of this system and the influence of different factors to the system, such as the differentiation between internal and external leakage, the control of the time influence in the system or the external condition influence in control.

In order to increase the knowledge of these two systems and their relation with the system variables, different tests were developed. These tests can be divided into two main groups; the first ones were related with the moisture alarm behaviour in different moisture conditions (related with time, volume and dimensions) while the second group was related with the pipe isolation water absorption for different salt concentrations.

The combination of these tests have made the perception of the importance of the time control in the moisture alarm possible due to the facts that the moisture is transferred through the isolation with low speed ratios and that the moisture alarm has showed some limitations. At the same time the study of the alarm reaction to different moisture states has shown a relation between the moisture conditions and alarm results.

These results make the idea of a future better knowledge of the network real state based on the time control, the variables study and the moisture alarm reaction possible. But in order to be able to reach this knowledge, some other studies and tests related with the moisture alarm are needed.
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1 Introduction

Heat generation, as a human need, has been a constant issue along history, since the fire’s invention to the nowadays systems, heat has always been needed for different necessities and it has been created in several ways.

Along the last centuries the heat generation has reach a point far from just the need of it in a survival context. The heat is used, despite the classic thermal comfort usage, in several industrial processes, from the creation of steel to the electricity generation. On the other hand, the heat, as one of the basic energy sources, is generated as waste energy in several other processes, i.e. the waste heat in a blast furnace, or the heat generated with a light bulb.

Those facts, with the limited sources in earth and the increasing world population, create the necessity of a sustainable way to generate and manage the heat. Hence, the engineering has been in a constant search for the performance improvement for several decades.

1.1 The district heating as a high performance heat generation system

Due to this need of an efficient system for the heat generation, the district heating was developed in the end of the S.XIX. Since that primary design, this system has had a technological and commercial implosion in different countries.

Briefly, a district heating consists of a conventional water boiler with enough power to transfer heat to a large quantity of customers. The choice of using a big high efficiency boiler to heat water just before it is shared across a network, rather than a single small boiler in each heat-demand point, allows the heat generation a higher performance.
At the same time, that allows the usage of different types of energetic sources to generate the heat. Thus, from an environmental point of view, the heat in the district heating can be generated, besides with the conventional fuels, also with biofuels, biomass or even with waste heat from other industries.

These points have made the district heating system one of the most used ways to generate heat in several countries. According to “Euroheat & power org” the district heating penetration can reach points of 95% in Iceland and between 50% and 60% in countries such as Sweden, Denmark and Poland (See Figure 1).

![Figure 1: District heating penetration by countries](image)

At the same time, the benefits of this heat generation system are motivating an increase in the usage of this technology, as can be shown with the tendency of the installed power in the Nordic countries since 1980 to 2006 (See Figure 2)
That is why, due to the constant and progressive expansion of this heat generation system, and in order to increase the performance of it, new challenges will be offered the engineering in the future.

**1.2 District heating: generation and distribution**

It is possible to divide the district heating into two different crucial functions. The first one can be called the “heat generation”, where the water is warmed up until the service temperature, whilst the second one can be considered as the heat transfer, in which the heated water has to be sent to the different consume points through a pipes network. The engineering issues around these two functions can be considered different, while the generation part deals with the search for the best way to generate the heat (in an economic and environmental context), the second one manage the heat losses reduction, the efficient water transfer and the constant control of the network.
For several years the research related with the district heating has been focused on the generation part, due to its importance in the system. Thanks to that, new heat sources and co-generation systems has been added to the “basic” district heating system, increasing significantly the efficient of it and reaching a point of high development. However, there has not been the same attention in the distribution system. Due to that fact, the technics of installation and control in this fundamental structure has remained the same for several years. The contrast between the high development in the heat generation and the low development in the heat transmission networks makes any research related with the network improvement interesting.

1.3 The heat distribution

In a district heating, the heat delivery is produced thanks to the pipes network, with which the heated water can reach every point. This network is a grid of isolated pipes, through them the heated water flows from the boiler to the consumption point. After the heat has been transferred in the demand point, the water returns to the boiler to get warmed up again.

Due to the size of these structures, from an engineering point of view, there is a large ratio of heat losses and possible malfunctions that must be controlled and minimized. Thus, the two principal issues in this grid are the minimization of the heat losses (see figure 3) and the control of the proper pipe’s behaviour, avoiding leakage and breaks. And while the control of heat losses in the pipes is a constant research topic in several science branches, the development of better control systems in the district heating networks is not a common research topic in these days.
1.4 The leakage control in the network: the moisture alarm

The control of the adequate operation of a DH network is an essential activity due to the several severe problems that can appear along its lifetime, such as a leakage in the pipe or corrosion problems.

Due to this necessity of a leakage control, a moisture alarm was developed in 1977 (US4013924-A patent). This system consisted of two copper wires (1.5 mm²) embedded in the isolated pipes and fittings. These wires make the moisture detection possible thanks to an electrical resistance drop (between the wire and the internal steel pipe) that is created when the moisture is emplaced between the wire and the pipe. In that way, by sending an electric signal through the wires and monitoring the resistance, it is possible to control the moisture state inside the isolation. Different improvements have been done since the first design, such as the usage of a time-domain reflectometer in order to be able to localize the moisture points.
Despite the new equipment and technic that has been developed since the first patent, there are still issues related with the moisture alarm control not solved yet.

Some of the several problems, not yet solved are:

- Low accuracy in the detection of the moisture (proportion and position).
- Scarcity in the knowledge of the real pipe’s state.
- Differentiation between internal and external leakage.
- Relation between the periods of time the moisture is emplaced in the insolation and the alarm detection of it.
- Inexistence of a standard method.
- Alarm reaction to different kinds of water.
- Differences between expected control results and field experience.
2 Objective and limitations

This project hopes to be a first approach in a deeper future study about these problems and, in that way, be helpful for the system improvement.

The studies enclosed in this master thesis deals with the effectiveness of this alarm system. The main objective deals with the study of the relation between the moisture alarm behaviour and the real state of the pipes. Following this line, different test were carried out over standard district heating pipes (pre-isolated). Some of the different parameters that were taken into consideration were the humidity ratio, the time relation, and the alarm reaction to the water.

At the same time, it is possible to differentiate two different studies in this master thesis. The first goal (and the starting point of this work), was the study of the TDR (wideco) behaviour in different moisture states in pre-isolated pipes, while the second aim was the study of the moisture absorption for the PUR foam which is usually installed in the pre-isolated pipes.

It is also of importance to mention the interest related with the creation of information related with this moisture alarm in such a language as English, due to the scarcity of English-spoken documents related with this issues.

Regarding to the thesis limitations:

- The proximity of the tests with the real failure cases: The isolated pipes used are not connected to a DH network installation, thus the test pipes do not have a heat stream, which affects on the temperature of the isolation and the working conditions of the moisture alarm.
• The unexpected water permeability of the isolation: It was generating null results in several tests.

• The time limitation: Some of the failures in a real network can be undetected for year, with all the connotations it supposes to the pipe, the isolation and the moisture alarm. In this thesis the each test were carried put with a time limitation.
3 Theoretical Foundation

3.1 The district heating network

In most cases the district heating stations supply heat to rather large areas, which suppose the necessity of several kilometres of pipes for each network (e.g. The Gävle district heating has 2x330 Km of conduits). As a rule, the network lines are usually buried or at least hard to reach.

The networks are based on the connections of pre-isolated conduits. There are two main types of pipes usually installed in a standard network, the single (see figure 4) and the twin pipe (see figure 5). Every pipe is connected with a joint system, such as a band muff (see figure 6). The single pipes are composed of an internal steel conduct (through which the DH water flows). This conduct is surrounded by an isolating foam (PUR and the foam is at the same time wrapped in a plastic cover. These networks are sensitive to possible construction or installation problems, defective joints, external damages, the mechanical wear or the corrosion.
3.2 The moisture alarm installation

The standard alarm system in countries such as Sweden or Norway is based on two wires (Φ 1.5 mm² soft copper wire) embedded in each pre-insulated pipes and joints. These wires are emplaced parallel to the pipeline and usually in the positions of 2 and 10 o’clock (see figure 7).

In order to achieve a proper monitoring, the wires are grouped in regions of a concrete length, also called loops, and at the same time each loop is connected to the pertinent measuring equipment.
Thus, each region is composed of the monitoring equipment and a wire loop that goes through the pipe’s isolation, both connected. The wire runs from the starting point to the further point of the loop and turns just after reaching that point, going back to the equipment. Each loop is created in this way. (See figure 8 &9).

There are two technics to install and connect these alarm system:

- **Two-wires or closed system;** where the wire stars and finishes in the same district heating line, which means that the entire loop is in the same sheath tube. This connection system supposes the need of two loops, one in the supply line and the other in the return line (See figure 8).

![Figure 5: Connection principle in a two-wires system [11]](image)

- **Open system;** one copper wire installed through the supply stream is connected to another wire in the return line, making one unique loop. This solution allows the control of distances twice as long than with the closed system, but as side effect this system can experiment some accuracy reduction (see figure 9).
Figure 6: Open system, the wires in the supply and the return lines are connected in one loop [11]

These loop installations, across the entire network, allows the monitoring of the pipes from a resistance meter principle.

3.3 **Physic properties related with the moisture control**

Before starting to lay the base of the moisture alarm principle, there are several factors related with the measurement principle.

3.3.1 The loop resistance

The study of this resistance has two main utilities. The first one is related with the state of the wire loop, since it is possible to check the appropriate state of the wires with this resistance, while the second one supposes a method to measure the distance between the loop beginning and the point with moisture.
This resistivity is based on the electric properties of the copper wires, which usually have an area of 1,5 mm\(^2\) and are normally working at an average temperature of 60\(^\circ\)C. The resistivity of the copper\(^1\) at a temperature of 20\(^\circ\)C is \(\rho = 0,0172 \, \Omega \cdot \text{mm}^2/\text{m}\) while the resistance alteration due to the temperature is sized with the proportion of \(\alpha = 0,0068 \, \Omega/\text{degree}\).

Thus, the copper wire resistance per meter, and the resistance variation due to the temperature can be expressed with the following equations:

\[
^2R_0 = \frac{\rho \times \text{Length}}{\text{Area}}
\]

\[
^3R = R_0 (1 + \alpha (T - T_0))
\]

Were: \(R\) is Resistance value; \(T\) is Temperature; \(\alpha\) is Temperature coefficient and \(\rho\) is copper density.

With these equations and the average boundary conditions of the district heating networks, it is possible to estimate the loop resistance in different conditions, which is showed in table 1 (See table 1).

<table>
<thead>
<tr>
<th>Temperature in wire ((^\circ)C)</th>
<th>R ((\Omega))</th>
</tr>
</thead>
<tbody>
<tr>
<td>70</td>
<td>1,54</td>
</tr>
<tr>
<td>65</td>
<td>1,50</td>
</tr>
<tr>
<td>60</td>
<td>1,46</td>
</tr>
<tr>
<td>55</td>
<td>1,42</td>
</tr>
<tr>
<td>50</td>
<td>1,38</td>
</tr>
<tr>
<td>45</td>
<td>1,34</td>
</tr>
<tr>
<td>40</td>
<td>1,30</td>
</tr>
<tr>
<td>35</td>
<td>1,26</td>
</tr>
<tr>
<td>30</td>
<td>1,22</td>
</tr>
<tr>
<td>25</td>
<td>1,19</td>
</tr>
<tr>
<td>20</td>
<td>1,15</td>
</tr>
</tbody>
</table>

\(^1\) [http://hyperphysics.phy-astr.gsu.edu/hbase/electric/restmp.html]
\(^2\) Electrical resistance of a conductor
\(^3\) Electrical resistance variation due to temperature
3.3.2 The isolated-wire resistance

As it is showed in the pictures above, the wire, which is going to make possible the moisture control, is totally surrounded by a thermal isolating. The most widely used isolation material for the pipe’s network is the polyurethane (PUR) foam. This material, used because of its thermal isolation characteristics, is also a good electrical insulating and catalogued as a dialectical material.

In a practical case, it is possible to say that the wire is totally isolated and that the electric resistivity will only decrease in a wet-state of the isolation.

3.3.3 Polyurethane electric resistivity

The polyurethane, since it is a dielectric material, can be represented as parallel resistances and capacitances (See figure 11). The capacitance and resistance of a piece of material often depends on the applied voltage frequency (Von Hippel, 1954). These characteristics generate a great resistance value between the alarm wire and the steel pipe in a dry state.

![Equivalent electrical diagram](image)

**Figure 7:** Equivalent electrical diagram for a dielectric material (a) and corresponding phase shift diagram (b).

---

4. The electric resistance of different materials are given in the section 3.4
3.3.4 Moisture absorption behavior for a polyurethane foam

In order to be able to study the moisture dynamic through the pipes isolating, the knowledge of the moisture absorption in standard PUR foam is needed. It is possible to know the relation of the moisture gain and the time for a piece of a PUR foam 20mm thick, submerged in water (20°C) (See figure 11).

![Figure 8: Moisture gain for a PUR foam 20mm thick [12]](image)

3.4 Moisture control bases

Once some of the factors related with the moisture control have been introduced, it is possible to base the moisture control principles. The moisture control is based on two technologies, the resistance drop control and the TDR usage to locate the moisture zone.
3.4.1 Resistance meter principle

This principle is based on a resistance drop between the alarm wire and the internal stream duct when the isolation is sufficiently wet (See figure 12).

Figure 9: The principle of fault defection using sensor wires

As has been said before (see figure 7), the PUR foam is emplaced between the alarm wire and the internal steel pipe (which makes the ground function). Due to the fact that PUR is a dielectric material, it is possible to represent the resistance between the copper wire and the internal tubing as an infinite number of parallel resistances and capacitances (See figure 13)

Figure 10: Electric equivalent circuit for the pre-insulated pipe
When water penetrates the insulation between the carrier pipe and the alarm wire, both resistance and capacitance, are affected. With the water as a conductive material, the resistance decreases and the electric current goes through the insulating foam. By motorizing the “measured resistance” (R mät) it is possible to keep an effective moisture control.

3.4.2 Principle of the time domain deflector (TDR) as

The resistance control allows controlling moisture state in the network, but it cannot give information about the failure emplacement. In order to be able to estimate the moisture point location, a TDR can be used. The principle of the time-domain reflectometer is based on the reflection generated from a transmitted impulse that has been sent through an electrical line. These reflections can be plotted and analysed in a graph. With this technic, the TDR sends out a voltage pulse over the alarm wire and the internal steel pipe. The reflection in the line is measured with high voltage and time resolution and it is usually visualized as a graph. In the graph it is possible to appreciate the voltage change. Disturbances like moisture, variation in the distance between the wire and the pipe, or the wire interruption cause changes in the electrical impedance of the line, creating reflections that can be displayed in the graph (See figure 14).

The physic property related with the TDR is the dielectric constant, which is defined as a measure of the material ability to store energy. It is different for every material and has a direct relation with the created reflections (different dielectric constant generates new reflections in the graph).
Due to the different dielectric constant hold by the polyurethane and the water\textsuperscript{5}, it is possible to trace the fail point in a district-heating network with the TDR technic.

### 3.5 Material data

#### 3.5.1 Materials conductivities

The conductivity of the PUR installed in the networks is related with its density. The polyurethane in the networks pipes is installed in a foam state, thus the conductivity of this is related with the foam relative density (See figure 15). The bulk PUR density is 1200 Kg/m\textsuperscript{3}.

\textsuperscript{5} Dielectric constant in different materials are given in the section 3.5.2
When the moisture is emplaced in the isolation foam, the conductivity changes drastically, making the moisture control possible. The resistivity and conductivity of different types of material related with the moisture control are shown in the following table (See table 2).

Table 2: Conductivity and resistivity of different materials [12]

<table>
<thead>
<tr>
<th>Material</th>
<th>Conductivity (mS/m)</th>
<th>Resistivity (Ω*m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deionized water</td>
<td>0,01</td>
<td>10^3</td>
</tr>
<tr>
<td>District heating water</td>
<td>&lt;1,0</td>
<td>&gt;10^3</td>
</tr>
<tr>
<td>(without oxygen)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Drinking water</td>
<td>25</td>
<td>40</td>
</tr>
<tr>
<td>Sea water</td>
<td>1000-4000</td>
<td>1-0,25</td>
</tr>
<tr>
<td>Copper wire</td>
<td>5,96*10^{10}</td>
<td>1,7*10^{-8}</td>
</tr>
<tr>
<td>Air</td>
<td>3*10^{-15}</td>
<td>3,3*10^{16}</td>
</tr>
</tbody>
</table>
3.5.1.1 Relation between salinity, temperature and conductivity

Some of the failures in the district heating networks can be emplaced close to a seawater zone. That makes some knowledge about the real relation between the sail content of the water, the temperature of this and the conductivity interesting.

Seawater typically has a salinity of around 35 g/Kg in contrast with the Baltic Sea\(^6\) water, which has a salinity of 10 g/L (PSU). The salinity proportion and the temperature affects the water conductivity which is shown in the table (See table 3)

<table>
<thead>
<tr>
<th>Proportion of NaCl in water (g/l)</th>
<th>Electrical Conductivity at 25 ºC (K_{25}^\circ C) (S/m)</th>
<th>Electrical Conductivity at 5ºC (K_{5}^\circ C) (S/m)</th>
<th>Temperature Relation (%/ºC)</th>
</tr>
</thead>
<tbody>
<tr>
<td>5</td>
<td>0,92</td>
<td>0,57</td>
<td>1,94</td>
</tr>
<tr>
<td>10</td>
<td>1,75</td>
<td>1,06</td>
<td>1,88</td>
</tr>
<tr>
<td>15</td>
<td>2,53</td>
<td>1,57</td>
<td>1,90</td>
</tr>
<tr>
<td>20</td>
<td>3,27</td>
<td>2,05</td>
<td>1,88</td>
</tr>
<tr>
<td>25</td>
<td>3,98</td>
<td>2,49</td>
<td>1,88</td>
</tr>
<tr>
<td>30</td>
<td>4,71</td>
<td>2,94</td>
<td>1,88</td>
</tr>
<tr>
<td>35</td>
<td>5,37</td>
<td>3,37</td>
<td>1,86</td>
</tr>
</tbody>
</table>

3.5.2 Dielectric constant

The dielectric constant is dimensionless and its function can be best understood through its relationship with other variables in a relationship equation. By defining the relationship between the capacitance of a capacitor dielectric with a specific capacitance of the same

capacitor with air, which has a dielectric constant of 1, the relative dielectric constant $k_e$ is obtained (See table 4).

Table 4: Relative dielectric constant for different elements

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative dielectric constant $^7$, $K_e$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Air</td>
<td>1</td>
</tr>
<tr>
<td>PUR isolation</td>
<td>1,2</td>
</tr>
<tr>
<td>Water with a temperature of 100ºC</td>
<td>56</td>
</tr>
<tr>
<td>Water with a temperature of 70ºC</td>
<td>64</td>
</tr>
<tr>
<td>Water with a temperature of 20ºC</td>
<td>80</td>
</tr>
</tbody>
</table>

$^7$ The relative dielectric constant is defined by the ratio between the dielectric constant in the material and the dielectric constant for the air. The air dielectric constant is $\varepsilon_0=8.854*10^{12}$ F/M.
4 Method

4.1 Methodologies

The two different goals studied in this thesis supposed the necessity of two different approaches. The approach, in order to achieve the first goal, was based on the usage of a TDR and the resistance control to study the moisture state in an isolated pipe. The second studies were accomplished controlling the weight increase of the isolation due to the water absorption.

4.2 Experimental apparatus and designed tests for the moisture detection with TDR and resistance control

The studies related with this part of the thesis were performed in two single pre-isolated pipes, each one with different diameter and alarm wire position. In order to be able to do as many test as possible, the two pipes were cut in different pieces of the same length. After the cut process the final number of pipe-pieces were: 4 pieces of 12.5 cm diameter (See figure 16) and 2 pieces of 20 cm diameter (See figure 15).
Different assemblies were designed in order to simulate, as close to reality as possible, a moisture state in the pipes. Three assembles or technics related with the moisture control were used.

4.2.1 Methodology 1: waterline connected to a water tank

The first assembly tried to simulate a failure in a network pipe made for some external perforation (experience shows this is one of the most common failure case). This perforation was supposed to allow moisture to spread through the isolation foam, producing eventual moisture detection with the alarm system. A standard size of 10mm was stipulated for the perforation. The water was transferred from a tank (10L) to the drilled hole (10mm) with a waterline (See figure 17). This assembly was tested with the two pipes models (Test 1 for the 20D model and Test 2 for the 12,5D).
4.2.2 Methodology 2: waterline pressurized

The second method was based on a pressurized waterline in order to increase the water absorption in the isolation. A pressure of 4 Bar was applied. (See figure 18). In order to reach the stipulated pressure a bicycle pump with pressure gauge was used.

![Figure 14: Bicycle pump and waterline connected to the studied pipe](image)

4.2.3 Methodology 3: controlled water injection in the foam

The last technique was based on the direct water injection into the isolation foam. A syringe was used for that purpose. By controlling the volume injected, the emplacement and the contact areas, it is possible to study the behaviour of the moisture alarm. Different contact areas and water volumes (simulating different possible moisture states) were tested. The three main dimensions related with these studies are (See figure 19):

- The contact width between the internal steel conduct and the water (moisture accumulated) within the isolation (W).

- Pipe length under moisture influence (L_v).

- Distance between the wire embedded in the isolation and the internal conduit (h)
It is possible to differentiate the different tests according to the purpose of each one.

4.2.3.1 Accuracy of the moisture detection (Resistance measure and TDR)

The approach of this test was related with the study of the moisture alarm sensibility. It is possible to define the sensibility as the lower moisture state that can produce its own detection (either with the TDR or the resistance control). Two technics were used in these tests:

- The first one was based on successive small water injections. These injections started from the wire position and were successively going forwards to the internal conduit (doing a line following the $h$ direction). While these successive injections were executed the moisture alarm equipment was sending control signals and

Figure 15: Representation of the relevant dimensions in the moisture control (L, W, h)

Figure 16: Example for a water injection
plotting the results (See figure 20).

- The second technic was more focused on the TDR precision than on the resistance control. In that way, different water volumes were introduced in the PUR foam (between the wire and the internal conduit). The volume of the water was increased in the length dimension ($L_v$). It is important to mention the necessity of avoiding the simultaneous water contact between the alarm wire and the internal conduit.

4.2.3.2 Moisture alarm behaviour to different water accumulations

In order to study the moisture alarm reaction to the water state in the pre-isolated pipe, different tests were carried out. The main variables in these tests were the contact between the moisture and the internal conduct ($W$), the moisture length ($L_v$) and the water volume (which is function of length, width and distance between wire and conduit). In this way mechanical failures with different width ($W$) and length ($L_v$) were filled up with water. Every moisture state was tested with the moisture alarm resistance and TDR. Two widths (0.5cm and 1cm) and lengths from 0cm to 18cm were simulated.

4.2.4 Measuring equipment

Each installation was connected to a TDR from the company *wideco* (see figure 21). In order to simulate a pipe installation of 150 meters (which is the length needed for the equipment in order to be able to detect the moisture with accuracy), 135 meter of light cable (*EKK-LIGHT 3G 1,5 ERICSSON*) were connected in series to the TDR and the tested pipe (75 meters before the tested pipe and another 50 after it). With a computer connected to the TDR, and the software XTool4 (*Wideco*), the control of the

*Figure 17: A moisture alarm TDR from the company “Wideco Ab”*
moisture state was possible due to the fact that the results were plotted in a graph. In this graph it is possible to analyse the loop resistance, the TDR radar result, the resistance and voltage for every single pulse sent through the moisture alarm wire.

4.3 Moisture absorption for the PUR foam

After the tests based on the TDR moisture control were carried out, other tests were developed. The main intention of this second group of tests was to study the PUR foam behaviour when it is in contact with different types of water. Thus two pieces of PUR foam were submerged into water with different salinity. The study of the time lapse and the moisture gain of these pieces, allows knowing the relation between time and humidity in the PUR. The knowledge of the time relation allows the estimation of the time needed for an external leakage, to reach some point inside of the foam and its relation with the water type.

The tests (1 and 2) were based on the weight increase of two squared pieces of PUR foam when they are submerged in water with different salinity content for long periods of time. In these tests the water studied was freshwater (tap water) and water with an equivalent salinity of the sea water (35 g NaCl per litter).
5 Results

5.1 Moisture detection with TDR and resistance control

The results obtained in the moisture detection with TDR are aggregated in three types, according with the technic used to obtain moisture in the isolation and the consequent moisture detection.

5.1.1 Results for the methodology 1: Waterline connected to a water tank

These tests were based on a system composed of a water tank (10 litres) and a waterline to the drilled hole in order to transfer water to the isolation foam. The first test was carried out with the 20cm in diameter pipe, while the second test with the one with 12.5cm in diameter.

After running each test for a time lapse of 9 hours, no moisture detection was found. The moisture alarm kept stable all the time and the water tank had the same quantity of water as when the equipment started to send sequent control signals. A later physical analysis of the actual moisture in the foam revealed that the water was spread along the foam in a lower speed that expected, almost null.

5.1.2 Results for the methodology 2: Water line pressurized.

In order to accelerate the moisture propagation through the material, a pressured based system was used. A waterline with a small quantity of water was connected between the drilled hole and a cycling pump. After 24 hours with a constant pressure in the waterline of 4 bar, no water absorption had been reported.
5.1.3 Results for the methodology 3:

The results of each section related with this methodology can be divided in the resistance control and the TDR radar results. Often the test results are compared with the test result in the standard case (when the pipe is in perfect condition and there is no moisture inside it) and the short-circuit\(^8\) case (which simulates a total failure state without electrical resistivity).

5.1.3.1 Accuracy of the moisture detection

Using a syringe needle, starting from the wire position, and going straight forwards to the internal conduit the test was implemented. The equipment showed the resistance evolution with the water content and the distance between the water and conduit (See table 5).

**Table 5: Resistance alarm results for the injected water tests**

<table>
<thead>
<tr>
<th>Successive connected water injections 1 cm Length ((L_v))</th>
<th>Distance between water and conduit, (h) (cm)</th>
<th>Water volume, (V) (ml)</th>
<th>Resistance ((k\Omega))</th>
<th>Desistance decrement ((%))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1,67</td>
<td>0,15</td>
<td>50.000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1,34</td>
<td>0,3</td>
<td>51.000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1,01</td>
<td>0,5</td>
<td>52.000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0,68</td>
<td>0,7</td>
<td>53.000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0,35</td>
<td>0,9</td>
<td>54.000</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0</td>
<td>1</td>
<td>7.300</td>
<td>86%</td>
</tr>
<tr>
<td>Length ((L_v)) increased to 2 cm</td>
<td>0</td>
<td>1,5</td>
<td>22</td>
<td>99.96%</td>
</tr>
<tr>
<td>Short-circuit</td>
<td>-</td>
<td>-</td>
<td>3,4</td>
<td>100%</td>
</tr>
</tbody>
</table>

It is possible to appreciate how the resistance decrease as soon as the moisture contacts with the wire and the internal conduit, breaking the electric insulation (86\% of decrement). It is also remarkable how the resistance diminishes when the contact area \((L_v\) from 1 cm to 2 cm) increases.

\(^8\) The short-circuit case is created connecting the alarm wire and the internal conduit.
In the case where the moisture is emplaced between the wire and the internal conduit but never connecting these two parts (in order to study the TDR behaviour rather than the resistance variation), the results can be divided in two parts, the resistance measures and the TDR graphs. The resistance value is represented in the following table (See table 6).

Table 6: Resistance control results for different moisture accumulation cases

<table>
<thead>
<tr>
<th>Circle 5,5mm Diameter (perpendicular to L)</th>
<th>Length L (cm)</th>
<th>Water volume V (ml)</th>
<th>Resistance (kΩ)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>1,25</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1,5</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>2,5</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3,5</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>4,5</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>6</td>
<td>480</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>8</td>
<td>13.000</td>
</tr>
<tr>
<td>Circle 10mm Diameter (perpendicular to L)</td>
<td>2</td>
<td>2</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>4</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>6</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>8</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>10</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>12</td>
<td>12</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>15</td>
<td>50.000</td>
</tr>
<tr>
<td></td>
<td>16</td>
<td>16</td>
<td>50.000</td>
</tr>
<tr>
<td>Short-circuit</td>
<td>-</td>
<td>-</td>
<td>0,4</td>
</tr>
</tbody>
</table>

Due to the fact that these tests were done in two different pipes, it is logical to assume the resistance drop showed in the table (see table; 5,5mm Φ volume between 6 and 8) was a measure mistake⁹ (the water was not supposed to connect the wire and the conduit).

Secondly, the TDR reaction to the different moisture states is shown with the represented graph (See image 22). The red line represents the standard TDR curve for the pipe in a normal state, while the black line shows the TDR curve (the reflected pulse) for the tested moisture condition.

---
⁹ The water was not supposed to connect the wire and the conduit in the test related with the TDR accuracy
Figure 18: TDR radar reaction to different moisture states. From top to down: without moisture, with 3.5ml and 16ml.
The graph evolution shows the possibility of the moisture detection when the resistance control is not efficient. In this way the TDR radar can detect a moisture state when the water content emplaced within the isolation is over the 3,5 ml. It is possible to appreciate how the TDR detects the distance between the starting point and the moisture emplacement as 77,9 meters (due to the 70 meter of light wire connected before the tested pipes)

5.1.3.2 Moisture alarm behaviour to different water accumulations

It is possible to separate the test related with this study into two constants widths, each one with a progressive length increase. When the tests were carried out with a contact (W) of 0,5 cm the moisture alarm showed the following results for the resistance control (See table 7) and the TDR radar reaction (see figures 23 and 24)

Table 7: Resistance measurement values for different moisture conditions

<table>
<thead>
<tr>
<th>Length L (cm)</th>
<th>Water volume V (ml)</th>
<th>Resistance (kΩ)</th>
<th>Resistance reduction related with the previous value (%)</th>
<th>Equivalence with TDR graphs (Nº)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>50,000,00</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td>0,1</td>
<td>1</td>
<td>33,00</td>
<td>99,93%</td>
<td>-</td>
</tr>
<tr>
<td>0,2</td>
<td>1,5</td>
<td>23,00</td>
<td>30,30%</td>
<td>-</td>
</tr>
<tr>
<td>0,3</td>
<td>2</td>
<td>22,00</td>
<td>4,35%</td>
<td>-</td>
</tr>
<tr>
<td>0,4</td>
<td>2,5</td>
<td>19,00</td>
<td>13,64%</td>
<td>2</td>
</tr>
<tr>
<td>0,5</td>
<td>3</td>
<td>18,00</td>
<td>5,26%</td>
<td>-</td>
</tr>
<tr>
<td>0,6</td>
<td>3,5</td>
<td>18,00</td>
<td>0,00%</td>
<td>-</td>
</tr>
<tr>
<td>0,7</td>
<td>4</td>
<td>18,00</td>
<td>0,00%</td>
<td>-</td>
</tr>
<tr>
<td>0,8</td>
<td>4,5</td>
<td>18,00</td>
<td>0,00%</td>
<td>-</td>
</tr>
<tr>
<td>0,9</td>
<td>5</td>
<td>17,00</td>
<td>5,56%</td>
<td>-</td>
</tr>
<tr>
<td>1</td>
<td>6</td>
<td>18,00</td>
<td>-5,88%</td>
<td>-</td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>5,40</td>
<td>70%</td>
<td>-</td>
</tr>
<tr>
<td>3</td>
<td>8</td>
<td>4,60</td>
<td>15%</td>
<td>3</td>
</tr>
<tr>
<td>4,5</td>
<td>9</td>
<td>1,60</td>
<td>65%</td>
<td>-</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>1,60</td>
<td>0%</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>12</td>
<td>2,50</td>
<td>-56%</td>
<td>4</td>
</tr>
<tr>
<td>8</td>
<td>14</td>
<td>1,90</td>
<td>24%</td>
<td>-</td>
</tr>
<tr>
<td>10</td>
<td>16</td>
<td>1,10</td>
<td>42%</td>
<td>5</td>
</tr>
<tr>
<td>Short-circuit</td>
<td></td>
<td>0,17</td>
<td>84%</td>
<td>6</td>
</tr>
</tbody>
</table>
Figure 19: TDR radar reaction to different moisture states. From top to bottom: 1) Standard state (No moisture); 2) with 2,5ml of water; 3) with 8 ml of water
Figure 20: TDR radar reaction to different moisture states. From top to bottom: 4) with 10 and 12 ml of water; 5) with 16ml of water; 6) short-circuit state
It is remarkable how the evolution of the radar is not linear with the volume (in this case with the increment of L), instead the graph shows an evolution when the volume has changed enough to be detected. The incongruity between graphs 4 and 5, where the graph 5 should shows a worse moisture state than in case 4, can be considered as a possible measurement mistake from the equipment.

In the same way, if the contact surface is increased from 0,5 cm to 1 cm, the results for the resistance value (See table 8) and the TDR radar (See figures 25,26 and 27) are attached.

<table>
<thead>
<tr>
<th>Hole 1 cm Width; W</th>
<th>Length L (cm)</th>
<th>Water volume V (ml)</th>
<th>Resistance R (kΩ)</th>
<th>Resistance reduction related with the previous value (%)</th>
<th>Equivalence with TDR graph (Nº)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>0</td>
<td>0</td>
<td>50,000,00</td>
<td>-</td>
<td>1</td>
</tr>
<tr>
<td></td>
<td>0,375</td>
<td>2</td>
<td>15,00</td>
<td>99,97%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>0,75</td>
<td>3</td>
<td>12,00</td>
<td>20%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1,125</td>
<td>4</td>
<td>11,00</td>
<td>8%</td>
<td>2</td>
</tr>
<tr>
<td></td>
<td>1,5</td>
<td>5</td>
<td>4,70</td>
<td>57%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>1,875</td>
<td>6</td>
<td>2,80</td>
<td>40%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2,25</td>
<td>7</td>
<td>3,10</td>
<td>-11%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>2,625</td>
<td>8</td>
<td>2,40</td>
<td>23%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>9</td>
<td>2,50</td>
<td>-4%</td>
<td>3</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>11,55</td>
<td>1,40</td>
<td>44%</td>
<td>4</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>12,41</td>
<td>1,40</td>
<td>0%</td>
<td>5</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>14,13</td>
<td>1,50</td>
<td>-7%</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>17,57</td>
<td>2,10</td>
<td>-40%</td>
<td>6</td>
</tr>
<tr>
<td></td>
<td>14,5</td>
<td>18,43</td>
<td>0,85</td>
<td>60%</td>
<td>7</td>
</tr>
<tr>
<td></td>
<td>18</td>
<td>22</td>
<td>0,80</td>
<td>6%</td>
<td>8</td>
</tr>
<tr>
<td>Short-circuit</td>
<td>-</td>
<td>-</td>
<td>0,55</td>
<td>31%</td>
<td>9</td>
</tr>
</tbody>
</table>

It is possible to observe how the resistance value doesn’t follow a lineal evolution; the resistance value can increase or decrease. Nevertheless these resistance values under moisture conditions are in a range of values far from the non-moisture state value (the first moisture state generates a 99% of resistance decrement)
Figure 21: TDR radar reaction to different moisture states. From top to bottom: 1) Standard state (No moisture); 2) with 4ml of water; 3) with 9 ml of water
Figure 22: TDR radar reaction to different moisture states. From top to bottom: 4) with 11.55ml of water; 5) with 12.41ml of water; 6) with 17.57ml of water
Figure 23: TDR radar reaction to different moisture states. From top to bottom: 7) with 18.43ml of water; 8) with 22ml of water; 9) short-circuit state
The TDR graphs evolution shows the relation between the moisture state and the TDR reaction. As was pointed out before, the TDR graphs, the evolution along the moisture gain (progressive \( L \) increment) is not lineal; instead the graph evolves every certain volume increment.

### 5.2 Moisture absorption for the PUR foam

Secondly, regarding to the water absorption for the PUR foam, the evolution of the moisture gain for the two tests (with freshwater and seawater) is represented in the following graph (See figure 28). The trend lines related with the two tests are also plotted.

![Graph showing moisture gains evolution for a piece of PUR in seawater and tap water.](image)

**Figure 24: Moisture gains evolution for a piece of PUR in seawater and tap water.**
6 Discussion

The different tests performed, each one with different purposes, allows a better knowledge of the moisture alarms behaviour and the influence on it for different factors, such as time, water contact, failure position, water type, temperature, pipe model, among others.

Some of the factors related with the moisture detection and their importance for the system are introduced in the following sections.

6.1 Time influence in the moisture control

Due to the size and conditions of the district heating networks, the time factor is one or the more interesting for the moisture alarm. When a moisture condition is detected, initially there is not a direct relation between the failure initiation and that detection.

The results obtained with the method 1 (tank water) and the method 2 (pressurized) gives the idea that from the first moisture state to the actual detection with the equipment, several numbers of days can be needed. In this way, the time lapse needed for the moisture detection is related with:

- The PUR foam water absorption and transfer, the detection speed is directly related with the time needed for the water to move through the isolator\(^\text{10}\).

- Pipe characteristics, such as size, which affects the amount of time needed for the moisture to be transferred from the failure point to the detection area.

- The leakage position (e.g. a internal leakage can be detected faster than external due to the proximity of the internal conduit to the alarm wires).

\(^{10}\text{The moisture gain for the PUR foam is showed in the section 3.3.4; figure 11}\)
• The water salinity. With the moisture absorption tests, it has been discovered how the seawater (35 g/l of salt content) has a lower absorption speed than the freshwater.\(^{11}\)

• Wire alarms position in the pipes. As a result of this, it is possible to study the real moisture state in the foam emplaced between the wires and the internal conduit.

### 6.2 Moisture alarm accuracy

Relative to the moisture alarm accuracy, the results have shown the different function for the resistance control and the TDR radar analysis. On one hand it is needed a total contact of the water between the alarm wire and the internal conduit in order to be able to detect this moisture, while on the other hand, if the moisture is just emplaced between wire and conduit the TDR can detect the failure for lengths (L\(_v\)) over 10cm or with a volume of 3,5ml. The combination of these two technics with their different behaviours can help to the proper failure diagnosis in a district-heating network.

### 6.3 Moisture alarm behaviour to different water states

The results obtained during the different tests carried out allow a study of the moisture detection behaviour based on the different factors related with the moisture detection physics.

The resistance control follows a non-lineal evolution, due to the drastic reduction in the first moisture detection and the oscillation of the values along the different moisture tests.

\(^{11}\) The Moisture gain evolution is plotted in the section 5.2; figure 28
Nonetheless the R-value shows an inverse relation with the contact dimension (W) and the Length ($L_v$), as it is possible to appreciate in the following graph\textsuperscript{12}(See figure 29).

![Graph](image)

**Figure 25:** R-value evolution for the different moisture states in a logarithmic scale.

If the resistance value for the no-moisture detection state is discarded, it is possible to plot the resistance evolution with a lineal axis (See figure 30).

\textsuperscript{12} The resistance values are represented in a log$_{10}$ axis, due to the drastic R-value reduction with the moisture detection

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The graphics evolution shows a high sensibility to the length gain in a leakage state, while the contact surface (W) also has influence in the R-value reduction but in a lower proportion.

On the other hand, the TDR radar results showed a no-lineal evolution, which is related with the moisture accumulation length (Lv) and Volume (V). It is possible to compare the TDR reaction to moisture states with similar length (Lv) but different contact surface (W) (See figure 31).
Figure 27: TDR radar reaction to different moisture states. From top to bottom: 1) 0.5 cm width and 10 cm length of water; 2) 1 cm width and 10 cm length of water; 3) 10 mm diameter and 10 cm length of water.
In this case, the TDR doesn’t show a direct relation between the contact surface (W) and the plotted graph. This result and the previous studies related with the TDR show how this equipment allows a complementary technic in to the resistance, not only in the location of leakage points but also in the actual moisture state in the networks (e.g. in large leakages growing in the L, and h dimensions, the TDR allows the detection of the moisture earlier than with the resistance technic.)

In summary, it is possible to say that any resistance reduction supposes the existence of moisture connecting the wire alarm and the internal conduit, and at the same time, the range of decrement and the TDR graphs makes an estimation of the real moisture state inside of any pre-isolated district heating pipe (the quantity of moisture and position or even its shape within the foam) possible.
7 Conclusion

The different tests carried out with their respective results have emphasised the relevance of different factors in the moisture control.

One of the most important factors to take in consideration is the time control in the moisture detection. The existence of an unknown time lapse between any leakage beginning and its detection has been proved. Several variables rule over this time lapse such as the foam absorption, the moisture type or the wire alarm emplacement. A deeper knowledge of the time function in the district heating networks can be helpful in order to reach a good knowledge of the DH network and make a better control of the network leakages possible.

In the same way, it has been possible to study the relation of other factors, such as the moisture content and its emplacement, with the moisture control. The resistance value and TDR evolution allows the conception of moisture control as the functional evolution controlled for a concrete number of variables, making a deeper future study of the mathematical influence of the variables on the system possible.

In any case, the combination of the R-value control and the TDR graphs in relation with the known and unknown variables of the system allows a deeper knowledge of the district heating networks rather than a simple R-value control.

Furthermore, some other tests and studies can be proposed in order to increase the knowledge related with the moisture alarm system:

- Study of the time lapse between the beginning of the external leakage and the moisture detection. These tests could be performed with different pipe types.

- Relation of the water type in a moisture state with the TDR graphs and R-value.
• Differences in the detection time lapse between an internal and an external leak

The combination of all the studies already done and the several ones that can still be done makes possible the idea of a wide knowledge of the district heating networks based on the resistance value, the TDR analysis and the variables control.
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