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Calculation formulas and description for dimensioning pre – insulated piping

Investigating the potential utilization of pre – insulated pipe calculation methods in LNG applications

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Abstract

As the demand for liquefied natural gas increases globally there are many local emerging markets arising but the technology and the infrastructure is capital intensive. The plants include many piping solutions which need to be designed specifically for this kind of application. The objective of this work is to evaluate the potential of using a pre – insulated pipe dimensioning model, developed for Uponor Infra Oy, a market leading Finnish company in piping infrastructure manufacturing, for liquefied natural gas applications. The methods used during the study were research and mathematics based including researching European standards on pre – insulated piping and thermodynamic calculations to establish the method of calculating thermodynamic properties of pre – insulated pipes. The results indicate that there is a potential in using pre – insulated pipe dimensioning calculation methods for liquefied natural gas applications.

Keywords: Liquefied natural gas, Pipe dimensioning, Pre – insulated pipes, Thermodynamics

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1 Introduction

During the last couple of decade natural gas' importance as an energy carrier increased considerably versus traditional oil products in the European Union. However the increase of the presence of natural gas in the energy mix in countries importing natural gas resulted on dependency on uncertain factors such as infrastructure (pipelines), political issues with exporting countries, etc. These factors and the European Union's effort on decreasing energy dependency led to the rise of relatively new technologies such as the renewable energy related solutions as well as different utilization of the traditional energy carriers (increasing energy efficiency, decreasing emissions). This in some case lead to the spread of already existing technological solutions like the liquefied natural gas (LNG) which is being produced commercially since 1964 however the market started to rise in the European Union only in the recent years due to facts discussed before and decreasing domestic production of natural gas[1][2].Not only it started to rise but many experts and organizations as well as governments globally see it as possible solution for the issues with increasing dependency on natural gas import in the near future, predicting a rapid rise in the utilization of liquefied natural gas (LNG) in the traditional natural gas applications as well as an environmentally less stressful transportation fuel. However the LNG technology is enormously capital intensive because it has to be designed to cope with the cryogenic temperatures of the liquefied gas, any solution to reduce the costs of the application is constantly being investigated and developed [3].

1.1 Aim and scope

As explained before liquefied natural gas (LNG) market could rise to a significant level in the European Union in the following decade and already many investments are made in this area. During the following pages the potential of using the products and the pipe dimensioning method developed for the Finnish company Uponor Infra Oy for district heating systems in liquefied natural gas (LNG) applications is described. This method is based on a practical work with Uponor Infra Oy in the field of pre – insulated pipe dimensioning The thesis is limited to small and mid scale liquefied natural gas (LNG) applications and to thermodynamic calculation model, which means that no other point of view, i.e. economical or architectural, will be discussed or evaluated. The aim is to describe the pipe dimensioning method researched and investigate the potential of using it on LNG applications.

2 Background

2.1 Company

The company, the project was carried out with, is Uponor Infra Oy. Uponor Infra Oy is a market leader in Northern Europe in pipe solutions with operations in North America and Asia. The company was formed in 2013 as a result of a merger of the plastic and piping units of two well known Finnish companies, KWH and Uponor to combat the economic recession with a combined expertise of the two companies.

Uponor Infra Oy now is specialized in underground infrastructure and solutions for transporting water, air, gas, electricity and telecommunication lines.

2.2 Project

The project aimed to create a new version of the company’s pipe dimensioning software which is able to calculate thermal properties for underground as well as over – ground infrastructure such as heat loss, temperature change, cooling time, etc. for standardized as well as free choice physical properties. This project had two parts, researching standards on piping installations, solutions in order to comply a mathematical source for the programming which was the second part. This work describes the research and mathematical part of the project.

2.3 Basic formulas

The following calculations and formulas are grouped according to the type of thermo dynamical properties and if they are standardized or not.

2.3.1 Introduction to thermodynamics in piping applications

Some calculations and formulas are uniform and serve as a base for more in depth examination of the thermal properties of pipes. These formulas are used with the specific calculations later however they have to be stated before in order to be able to comprehend and reference them when needed.

For a multi – layer hollow cylinder the linear density of heat flow rate, q_{l} [W/m], in general is given by Equation (1):

$$q_{\mathrm{l}} = \frac{\theta_{\mathrm{si}} - \theta_{\mathrm{se}}}{R'_{\mathrm{l}}} \tag{1}$$

where

θ_{si} is the internal surface temperature [K]

θ_{se} is the external surface temperature [K]

R'_{l} is the linear thermal resistance [mK/W] given by Equation (2)

$$R'_{\mathrm{l}} = \frac{1}{2\pi}\sum_{j=1}^{n}\left(\frac{1}{\lambda_j}\ln\frac{D_{\mathrm{e}j}}{D_{\mathrm{i}j}}\right) \tag{2}$$

where

λ_j is the thermal conductivity of the material of layer nr. j [W/mK]

D_{ej} is the external diameter of layer *j* [m]

D_{ij} is the internal diameter of layer *j* [m]

Using Equation (1) the heat flow rate per meter, $q_{\mathrm{l,E}}$ [W/m], for a single underground multi – layered pipe can be calculated with some small changes shown by Equation (3)

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{i}} - \theta_{\mathrm{sE}}}{R_{\mathrm{l}}' + R_{\mathrm{E}}} \tag{3}$$

where

θ_{i} is the temperature of the medium [K]

θ_{sE} is the (assumed) external surface temperature [K]

R_{l}' is the linear thermal resistance of the pipe [mK/W]

R_{E} is the linear thermal resistance of the ground (homogeneous soil) [mK/W]

The linear thermal resistance of the insulation, R_{l}', is given by Equation (2) and the linear thermal resistance of the ground, R_{E}, is given by Equation (4) as follows

$$R_{\mathrm{E}} = \frac{1}{2\pi\lambda_{\mathrm{E}}} \cosh^{-1} \frac{2H_{\mathrm{E}}}{D_n} \tag{4}$$

where

λ_{E} is the thermal conductivity of the soil [W/mK], Table VI shows values for common types of soils encountered

H_{E} is the distance between the centre of the pipe and the ground surface [m]

calculated by Equation (5)

$$H_{\mathrm{E}} = H + \frac{D_{\mathrm{e}}}{2} \tag{5}$$

where

H is the distance between the pipe and the ground surface [m]

D_{e} is the external most diameter of the pipe [m]

In practice it is common to use a square cross section of the pipe and the surrounding soil. D_n is the square cross section of the outer most layer (the soil) considered with an equivalent diameter calculated by Equation (6)

$$D_n = 1.073 \times a \tag{6}$$

where

a is the side length of the cross – section [m]

2.3.2 Surface temperature

The surface temperature of the pipe, θ_{sE} [K], can be included in different ways. Under industrial application it can be measured directly while under manufacturing it can either be assumed based on the similar pipe type's data in active use or it can be calculated through a method where in Equation (3) ambient temperature, θ_{a} [K], is used instead of surface temperature to get the linear heat flow rate per meter, $q_{\mathrm{l,E}}$ [W/m], and after that Equation (7) to be used to calculate the interface temperature, θ_{int} [K]:

$$\theta_{\mathrm{int}} = \theta_{\mathrm{i}} - q_{\mathrm{l,E}} * R_{pipe} \tag{7}$$

where

R_{pipe} is the linear thermal resistance of the carrier pipe calculated by applying Equation (2) for only the inner most layer [mK/W]

Using the calculated interface temperature, the surface temperature can be obtained according to Equation (8):

$$\theta_{\mathrm{sE}} = \theta_{\mathrm{int}} - q_{\mathrm{l,E}} * R_{ins} \tag{8}$$

where

R_{ins} is the linear thermal resistance of the insulation of the pipe calculated by applying Equation (2) for every layer excluding the carrier pipe [mK/W]

3 Pipe dimensioning

3.1 Hot medium

3.1.1 Standardized district heating heat loss

The standardized pre – insulated single pipes has three given layers, as specified by standards, the steel or stainless steel carrier pipe, the Polyurethane (PUR) insulation foam and the Polyethylene (PE) casing. With these specifications Equation (3) can be used and calculated for three layers in Equation (2). The only variables therefore are the diameters which can be calculated from the standardized pipes inner diameter and wall thickness given in the standard and shown in Table I for the carrier pipe, in Table II for the insulation and in Table III for the casing[4]. The pre – insulated twin pipes specifications, which material wise are the same as mentioned before: steel carrier pipe, PUR insulation and PE casing, can be calculated using Equation (9) and Equation (10) which gives the heat loss per meter [W/m] as follows

$$q_t = 4\pi\lambda_{PUR}h_s\left(\frac{\theta_1 + \theta_2}{2} - \theta_0\right) \tag{9}$$

where

λ_{PUR} is the thermal conductivity of the PUR insulation (0.025 [W/mK])

θ_0 is the (assumed) surface temperature of the casing [Celsius]

θ_1 is the temperature of the medium in pipe 1 [Celsius]

θ_2 is the temperature of the medium in pipe 2 [Celsius]

h_s is the surface coefficient of heat transfer and is calculated by Equation (10) [W/m^{2}K]

$$h_s = \frac{1}{\ln\left(\frac{(r_1)^2}{2Dr_2}\right) - \ln\left(\frac{(r_1)^4}{(r_1)^4 - D^4}\right) - \frac{\left(\frac{r_2}{2D} + \frac{2r_2D^3}{(r_1)^4 - D^4}\right)^2}{1 + \left(\frac{r_2}{2D}\right)^2 - \left(\frac{2r_2(r_1)^2D}{(r_1)^4 - D^4}\right)^2}} \tag{10}$$

where

D is half the distance between the center of the twin pipes [m]

r_1 is the radius of the casing pipe [m]

r_2 is the radius of the inner pipe (the twin pipes have same dimensions)[m]

In this case the only variables are the temperature values due to the standardized dimensions of the pipe systems can be seen in Table I - III regarding the standardized pipes from DN 15 to DN 250 with the respected distances between the carrier pipes given in Table IV [5].

3.1.2 Heat loss

The following chapters aims to describe calculations and formulas for heat loss with different properties considering free – choice variables wherever it is possible which means that the value of most of the variables from that point on can be freely selected by the user.

Calculating heat loss for multiple layers (up till five layers in the project, but unlimited in theory) can be obtained using Equation (3) and Equation (2), Equation (4) respectively for single, underground pipes. Where the only set data is thermal conductivity, λ, of the soil and the different materials could be used in the layers of the pipes. These values are automatically set after choosing the materials. The thermal conductivity, λ, values and the emissivity, ε, values can be examined in Table V. The other values can be manually chosen in the beginning of the calculation procedure.

Calculating heat loss for pipes installed above ground shows some similarity with the heat loss calculation methods for the single, underground pipes however the effects of the surroundings of the pipe should be addressed, such as the effects of the wind on the heat transfer. The formulas for calculating heat loss in an above – ground pipe(section) can be obtained from Equation (3) with a slight modification as shown in Equation (11):

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{i}} - \theta_{\mathrm{sE}}}{R_{\mathrm{l}}' + R_{\mathrm{le}}} \tag{11}$$

where

θ_{i} is the medium temperature [K]

θ_{sE} is the external surface temperature [K], found in **Chapter 2.3.2**

R_{l}' is the linear thermal resistance of the insulation and can be obtained from Equation (2)

R_{le} is the linear thermal resistance of the external surface of the pipe and can be calculated using Equation (12) as follows:

$$R_{le} = \frac{1}{h_{se} * \pi * D_e} \tag{12}$$

where

D_e is the external diameter [m]

h_{se} is the outer surface coefficient of heat transfer and it is conditionally calculated depending on the outer diameter, D_e [m], according to Equation (13) and Equation (14) [W/m^{2}K]:

$$h_{se} = \frac{8.1 * 10^{-3}}{D_e} + 3.14 * \sqrt{\frac{v}{D_e}} \tag{13}$$

$$h_{se} = 3.96 * \sqrt{\frac{v}{D_e}} \tag{14}$$

where

D_e is the external diameter [m]

v is the wind velocity [m/s]

Equation (13) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (14) applies [6].

3.1.3 Temperature change

In the following chapter the formulas and calculation for temperature change of a flowing medium in a single on a selected distance will be discussed in detail.

For pipes laid underground the final value of the temperature change is given by Equation (15):

$$\left|\theta_{im} - \theta_f\right| \tag{15}$$

where

θ_{im} is the initial temperature [K]

θ_f is the final temperature obtained by Equation (16) [K]:

$$\theta_f = |\theta_{im} - \theta_a| * e^{-\alpha * l} \tag{16}$$

where

θ_i is the initial temperature [K]

θ_a is the ambient temperature [K]

l is the length of the pipe(section) observed [m]

α can be obtained from Equation (17):

$$\alpha = \frac{U_{tl} * 3.6}{\dot{m} * c_p} \tag{17}$$

where

$\dot{m}$ is the mass flow rate [kg/h]

c_p is the specific heat capacity of the medium [kJ/kgK]

U_{tl} is obtained from Equation (18):

$$U_{tl} = U_l + \Delta U_{bl} \tag{18}$$

where

ΔU_{bl} is calculated from Equation (19)

U_l is calculated using Equation (20)

$$\Delta U_{bl} = \frac{1}{l} \tag{19}$$

where

l is the length of the pipe (section) observed [m]

$$U_l = \frac{1}{R_l + \frac{1}{h_{se} * \pi * D_e}} \tag{20}$$

where

D_e is the external diameter [m]

R_l is the linear thermal resistance obtained from Equation (2) [mK/W]

h_{se} is the outer surface coefficient of heat transfer and it is conditionally calculated depending on the outer diameter, D_e [m], according to Equation (21) and Equation (22) [W/m^{2}K]:

$$h_{se} = 1.25 * \sqrt[4]{\frac{\Delta\theta}{D_e}} \tag{21}$$

$$h_{se} = 1.32 * \sqrt[4]{\frac{\Delta\theta}{D_e}} \tag{22}$$

where

D_e is the external diameter [m]

$\Delta\theta = |\theta_{se} - \theta_a|$

where

θ_{se} is the surface temperature of the pipe [K]

θ_a is the ambient temperature [K]

Equation (21) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (22) applies.

For pipes above the ground the calculation method is mainly identical to the way of the temperature change in a buried pipe is obtained. The only difference is in Equation (20) the value of the outer surface coefficient of the heat transfer, h_{se}, is calculated through Equation (13) and Equation (14) in conditional respect to the outer diameter, D_e, Equation (13) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (14) applies[6].

3.1.4 Cooling time

This chapter will detail the necessary formulas for calculating the cooling time in hours, inside of a single pipe in a given distance.

The cooling time for an underground pipe, t_v [h], is calculated according to Equation (23) as follows:

$$t_{\mathrm{v}} = \frac{(\theta_{im} - \theta_a) m c_p \ln \frac{(\theta_{im} - \theta_a)}{(\theta_f - \theta_a)}}{\phi_{\mathrm{T}} * 3.6} \tag{23}$$

where

θ_{im} is the initial temperature of the medium [K]

θ_f is the final temperature of the medium [K]

θ_a is the ambient temperature [K]

m is the mass of the content [kg]

c_p is the specific heat capacity of the medium [kJ/kgK]

ϕ_{T} is the total heat flow rate and is obtained from Equation (24):

$$\phi_{\mathrm{T}} = U_{tl} * l(\theta_{im} - \theta_a) \tag{24}$$

where

θ_{im} is the initial temperature of the medium [K]

θ_a is the ambient temperature [K]

l is the length of the pipe(section) observed [m]

U_{tl} is calculated according to Equation (18)

To be able to get to the results the steps presented with Equation (19), Equation (20), Equation (21) or Equation (22) should be followed resulting in the same conditional calculations respect to D_e, where Equation (21) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (22) applies.

In calculating the cooling time, t_{v},, it is assumed that no heat is absorbed by the media during cooling. The cooling time obtained on this basis is the fastest which means that there is a built in safety factor in the calculations for design purposes.

For calculating the cooling time, t_{v}, in a pipe above ground is given by Equation (23) and is being followed up by the formulas in order with Equation (24), Equation (18), Equation (19), Equation (20), Equation (13) or Equation (14). To reach a precise conclusion it has to be established that the same conditions apply here as well, namely Equation (13) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (14) applies[6].

3.1.5 Freezing time in pipes

The following chapter will discuss the special case of the cooling which is highly important in piping industry, the freezing time. It is not possible to prevent the freezing of a liquid in a pipe, although insulated, over an infinite long period of time given the ambient temperature is smaller than the freezing point of the liquid.

The total heat flow rate, ϕ_{T}, of a stationary liquid is determined by the temperature difference, the properties of the insulation and the geometry of the pipe. Also the energy stored in the liquid, $m_w c_{pw}$, and in the pipe material, $m_p c_{pp}$, as well as by the freezing enthalpy should be taken into consideration. If $m_p c_{pp} \ll m_w c_{pw}$, then $m_p c_{pp}$ may be neglected.

Therefore the general formula for the freezing time, t_{wp}, is given by Equation (25) as follows:

$$t_{wp} = \frac{(\theta_{im} - \theta_a)\left(m_w c_{pw} + m_p c_{pp}\right) \ln \frac{(\theta_{im} - \theta_a)}{(\theta_f - \theta_a)}}{\phi_{\mathrm{T}} * 3.6} \qquad (25)$$

where

θ_{im} is the initial temperature of the medium [K]

θ_f is the final temperature of the medium [K]

θ_a is the ambient temperature [K]

m_w is the mass of the content [kg]

c_{pw} is the specific heat capacity of the medium [kJ/kgK]

m_p is the mass of the pipe [kg]

c_{pp} is the specific heat capacity of the pipe [kJ/kgK]

ϕ_{T} is the total heat flow rate and is obtained from Equation (24)

To finalize this method the following formulas should be considered in order; Equation (18), Equation (19), Equation (20), Equation (21) or Equation (22) in case of a single, buried pipe, Equation (18), Equation (19), Equation (20), Equation (13) or Equation (14) in case of a single, above – ground pipe. To reach a precise conclusion it has to be established that the same conditions apply here as well as before, Equation (21) or Equation (13) is to be used accordingly if $D_e \leq 0.25$ [m] in any other case Equation (22) or Equation (14) applies[6].

3.2 Cold medium

During this part the different properties of pre – insulated pipes, pipe systems will be explained in further detail in respect to a cold medium in the pipe. That means the temperature of the flowing medium in the pipe has a smaller value than the ambient temperature therefore it will not release heat it will take it up instead. These calculations therefore are relevant for mostly cooling procedures with pipe installation.

The methods and the formulas are almost identical to the ones explained before except the calculation of the condensation. Because of this in the main part this chapter the emphasis is on the introduction of the methods pointing out already existing formulas and the slight tweaks required for application in this case.

3.2.1 "Cold loss"

This part is describing the methods of calculating "cold loss" - a special case of heat loss when the flowing medium has a lower temperature than the surroundings - of a single pipe.

The method is completely identical to the calculation of heat loss except a small change in Equation (3) where the temperature values has been swapped which is shown in Equation (26):

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{sE}} - \theta_{\mathrm{i}}}{R_{\mathrm{l}}' + R_{\mathrm{E}}} \tag{26}$$

where

θ_{i} is the temperature of the medium [K]

θ_{sE} is the (assumed) external surface temperature [K]

R_{l}' is the linear thermal resistance of the insulation [mK/W] given by Equation (2)

R_{E} is the linear thermal resistance of the ground (homogeneous soil) [mK/W] given by Equation (4)

The thermal conductivity, λ, values and the emissivity, ε, values can be examined in Table V. The other values can be manually chosen in the program at the beginning of the calculation procedure.

To be able to obtain the right formula for above ground pipes Equation (25) and Equation (11) should be merged resulting in Equation (27) as follows:

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{sE}} - \theta_{\mathrm{i}}}{R_{\mathrm{l}}' + R_{\mathrm{sE}}} \tag{27}$$

where

θ_{i} is the medium temperature [K]

θ_{sE} is the (assumed) external surface temperature [K]

R_{l}' is the linear thermal resistance of the insulation and can be obtained from Equation (2)

R_{le} is the linear thermal resistance of the external surface of the pipe and can be calculated using Equation (12)

The method continues with the method established before with Equation (13) and Equation (14), where Equation (13) is to be used if $D_e \leq 0.25$ [m] in any other case Equation (14) applies

3.2.2 Temperature change

In order to see the method of the temperature change in a pipe(section) for a single, buried pipe **Chapter 3.1.3** should be used due to the method and the formulas used are identical and no change is needed in order to reflect the change in the direction of the heat transfer.

3.2.3 Condensation

Preventing dew formation is critically important in any kind of piping application using cold media because the condensation could lead to structural failure in the pipe itself. In the following section the method of determining minimum insulation thickness in order to prevent surface condensation and dew formation on pipes will be presented as well as the methodology of determining if a certain pipe in a certain condition is able to pass the criteria of being able to prevent dew formation or not.

The first step in order to calculate the minimum insulation thickness for dew prevention is the determination of the thickness parameter, *C’* [m], using Equation (28) as follows:

$$C' = \frac{2\lambda}{h_{se}}\left(\frac{|\theta_{im} - \theta_a|}{|\theta_{se} - \theta_a|} - 1\right) \tag{28}$$

where

λ is the thermal conductivity of the insulation [W/mK]

h_{se} is the surface heat transfer coefficient and is calculated according to Equation (21) or Equation (22) in case of a single, buried pipe or Equation (13) or Equation (14) in case of a single, above – ground pipe

θ_a is the ambient temperature

θ_{im} is the initial temperature of the medium

θ_{se} is the surface temperature of the pipe(section) and $|\theta_{se} - \theta_a|$ is obtained according to Table VII, given in the Appendix, where $|\theta_d - \theta_a| = |\theta_{se} - \theta_a|$

The result for minimum insulation thickness is gotten using the thickness parameter, C', and the diameter in accordance with Fig. 1 given in the Appendix .

To be able to determine if a pipe is able to prevent dew formation or not the first step is to check with Table VII, given in the Appendix, if the temperature difference between the surface and the ambient condition is acceptable or not. In case the conditions are satisfactory the minimum insulation thickness should be determined using Equation (28) and Fig. 1, given in the Appendix, and the results should be compared with the actual insulation thickness in question[6].

4 Case study: Using pre – insulated piping solutions for liquefied natural gas (LNG) applications

Liquefied natural gas (LNG) is a clear, colorless and non – toxic liquid which forms when processed natural gas is cooled to approximately – 162 °C. In liquid form natural gas takes up about 600 times less space than in gaseous form. Also worth mentioning that liquefied natural gas (LNG) will not ignite while it is in liquid state and when it is vaporized will only ignite when mixed with air in concentrations of 5% to 15%.

Due to its gaseous state natural gas is immanently a domestic product. As a gas the only sensible way of transportation is through pipelines, however this reduces the number of end users. Liquefied natural gas (LNG) was developed as a solution to this problem and was commercially introduced in 1964 when the world’s first commercial LNG plant in Arzew, Algeria started production[7]. The first commercial cargo was shipped out the same year to the United Kingdom.

Liquefied natural gas (LNG) has changed the natural gas market because it made previously unrecoverable (for many reasons including i.e. economy or politics) gas reservoirs feasible for production.

4.1 Liquefaction

The composition of the natural gas determines how it will be processed for transport. Either staying in gaseous state or being liquefied natural gas from the well has to be separated from water, acid gases and heavy hydrocarbons. The following steps during processing are defined by the transportation system being used. For liquefied natural gas (LNG) additional processing is needed before the condensation procedure to remove the risk of crystallization in the heat exchangers inside of the liquefaction plant. In case chemical conversion is used to liquefy natural gas the conversion process will determine what other preliminary steps should be used. Additionally a method called fractionation is used to separate the heavy hydrocarbons from methane during the liquefaction process so that after re - gasification the gas could be loaded into the distributing pipeline network.

Natural gas is liquefied by cooling the energy carrier to approximately – 162 °C, this drop in temperature making it possible to have liquid state methane at atmospheric pressure. After liquefaction LNG usually get loaded into tankers or into a storage tank. During transportation and storage the LNG is kept in its liquid form by keeping the cryogenic temperature the gas has been liquefied on. However a small part of the LNG cannot be kept from boiling, this gas is called boil off gas (BOG) and usually captured and used as a fuel for the tanker the LNG is transported on. When the LNG reached its destination it is either gets stored, transported and used as a fuel or re – gasified. During the re – gasification process the LNG is dehydrated into a gaseous state again by a process involving sending the LNG through a series of vaporizers that reheat the gas above the – 162 °C temperature. The gas is then utilized in the traditional ways by entering the local gas distribution network, the pipelines [8].

4.2 Application

Liquefaction and re – gasification facilities are still limited in number however there are several projects ongoing worldwide including i.e. LNG projects in the Netherlands in the European Union. The Middle East is the dominant LNG exporter world wise according to data from 2010. Other major LNG exporting countries are situated in South East Asia and the Middle East. In Europe, not considering the Russian Federation, Norway is the leading LNG exporter. Traditionally some of the largest importers of LNG are Japan and South Korea which countries almost entirely depend on liquefied natural gas to cover their natural gas demand. Also European countries, mainly European Union member states, are importing a large percentage from the globally produced LNG. Emerging markets for liquefied natural gas are China and India where natural gas related projects are pursued currently and they are already present amongst the top importers [9].

There are two main applications of liquefied natural gas. One is the traditional use of LNG as natural gas supply. In this case the LNG will be re – gasified and pumped into the distribution network to reach the end user. In this application the reasons to use liquefied natural gas have touched before, they are mainly economical or political. As an example the European Union member states can illustrate most of these aspects. The EU thrives to become less energy dependent but regarding natural gas its main source of import is the Russian Federation through pipelines. This has become a few times extremely stressing for EU members when political issues rose. The most recent example is the conflict in Ukraine which cooled the relation a little bit between the European Union and Russia. That is one of the reasons why LNG import and traditional application are increasingly important to the EU. The other reason for using LNG as a transportation solution is simple economics from the exporter’s point because this method makes gas fields that were not economically feasible to extract able to start production because the transportation does not depend on the construction of pipelines. In fact there are some already existing solutions for a mobile LNG plant called FLNG plant: “Floating LNG plant”. The other, relatively new, application of liquefied natural gas is simply using as transportation fuel either for shipping or road transport.

Regarding the EU new environmental regulations started to apply in order to reduce emissions from ships. These regulations are even stricter near ports. Since LNG as a fuel is almost completely free of sulphur and particulates it can help to comply with these strict requirements. LNG fuel could be used by ferries, barges, cruisers and tug boats. In fact ferries running with LNG are already being used on inland waters in Norway. Also the technology that has been mentioned before, where the boil off gas (BOG) from LNG tankers is collected and used as a fuel to power the ship has been implemented on many tankers. As well as the technology which makes these tankers able to use the LNG they are carrying as a fuel when inside the emission restriction zones.

LNG has a potential to reduce fuel cost due to better fuel efficiency compared to traditional diesel in road transportation which could lead to a feasible alternative for traditional fuels especially in the long distance transportation. Also because the before mentioned less sulphur and particulate content in comparison with diesel it could offer an alternative in public transportation in cities as well. The use of different kind of forms of methane is already in use in several EU countries, i.e. the use of biogas in buses in Sweden, so the potential is already being realized in the public transportation. Regarding the long distance road transportation the technology is relatively new therefore the infrastructure is not quite established yet, meaning there are not enough LNG fuelling stations across the EU. However trends are showing the willingness of truck manufacturers as well as petroleum companies to develop the technology by building more and more LNG refueling stations as well as developing LNG powered vehicles.

As per the perspective of pipe dimensioning LNG applications use pipes with varying dimensions, function and size depending on the specifications of the applications. These can include piping in – plant, out – plant and even pipelines just as the natural gas ones. It is quite obvious that the material and size specifications highly different in the before mentioned cases. In – plant piping usually have vacuum jacketed metal pipes ranging in external diameter from 48 to 130 mm which can be considered quite small. Outside piping usually have bigger difference in size depending on the actual size of the plant and function of the pipe however it can be concluded that usually it ranges from mid to large external diameter pipes which either pressurized or non – pressurized but they are insulated most of the times but there are applications with vacuum jacketed pipes as well. Special cases are the off – shore LNG plants which are the results of relatively new ideas to overcome time, cost and environmental regulations in port. These plants are basically similar LNG plants like the on – shore ones except that they are out on the sea therefore the issue of transporting the gas inland is solved by traditional pipeline method. From these off – shore plants LNG either is getting re – gasified and transported with the traditional pipelines or it is getting transported in its liquid phase which means that the pipes constituting the pipeline are either pressurized pipes or well insulated ones.

4.3 Environmental perspective

There has been debated and written much about the carbon footprint of oil and natural gas compared to each other. The main debated issue is that while oil and its products are transported through the globe via tankers while natural gas is transported through pipelines resulting in smaller carbon footprints during transportation. The role of pipelines is decreasing as mentioned before, with LNG operations on the rise. The processes and infrastructure regarding LNG are highly capital intensive however. The clear advantage of LNG lies in the distant markets which are not economical for pipelines usually longer than 3000 km. Energy usage and emissions are debatably the areas where natural gas via pipelines can have an environmental advantage over LNG but this advantage is highly dependent on different design factors. The efficiency of pipelines decreases with the length increase. This is true for greenhouse gas emissions as well. LNG compared to pipelines on shorter distances the pipelines come out far more environmentally friendly however as the distance increases the greenhouse gas emissions from the pipelines increase rapidly due to the escaping methane that are inevitable on longer distances. Because of that the emissions from the pipelines during transportation equalizes the emissions from LNG transportation on a distance approximately 7500 km [10]. The quality of the gas from LNG could be better than from the pipelines due to impurities are mostly removed during the liquefaction process but the environmental impacts of the two forms of natural gas rely on how effectively appliances are designed for these gases. Since LNG is a relatively new concept (regarding the spread) not many appliances designed such a way to be able to utilize fully the advantages of gas from LNG. As an example of this a study conducted in England showed that appliances that are designed for handling pipeline gas can emit more nitrous oxides when they run on re – gasified LNG. However as technology advances the situation may change with time due to LNG more significant role in the global gas market which possibly going to sparkle more and more advance in the field regarding efficiency and emissions[11].

4.3.1 Liquefied Biogas (LBG)

As mentioned before one of the main applications of LNG is as a fuel in vehicles. For this purpose a concept was developed recently based on biogas production where the biogas is converted into liquid state using the same technology applied during LNG production, namely, liquefaction in a condensation plant where the temperature is lowered to – 162 °C at atmospheric pressure. This liquefied biogas (LBG) is then used as a fuel in public transportation buses. One such a plant situated in Lidköping, Sweden where biogas is being produced from local vegetable waste products from grain trade and food production. The plant also produces compressed biogas (CBG) which also being used as transportation fuel. The technology used in the plant in Sweden includes an additional step in the liquefaction process where carbon – dioxide is being removed from the biogas. Due to the production of compressed biogas the plant is able to produce liquefied biogas on higher temperatures by raising the pressure making it possible to create LBG on – 140 °C at 4 bar [12]

5 Pre – insulated pipes in LNG applications

5.1 Methods

The methods used have to be separated according to fact that the practical part and the pipe dimensioning required different methods. During the practical part as mentioned before the main method was research in different standards regarding pipeline solutions, mostly in the field of district heating. After the research the gathered information, data, formulas and calculation methods had to be complied into a sensible source for the programming of the pipe dimensioning tool. For the compilation basic methods has been used such as writing them down and traditional MS Office tools like MS Excell. Then the compiled model was applied in the case of a liquefied natural gas application to evaluate if the model is applicable. Whenever an assumption has been made it will be indicated before of the regarding part.

5.2 Dimensioning pre – insulated piping in LNG applications

Due to the specifications of the liquefied natural gas the segments of the model to be used are the following; “cold loss”, temperature change and condensation. The “cold loss” calculations would be able to show an overall thermodynamic efficiency for the different pipes in under the extreme conditions that come with the LNG handling. The temperature change values can be used in order to get an overview on the distance in a certain pipe the liquid could travel without reaching its boiling point, which then shows how the design of the whole pipe system should be done to avoid boiling. The most important values regarding LNG and pre – insulated piping are under the condensation part because if dew formation happens it can structurally damage the pipe radically in extreme temperature such as the approximately -160 C° the LNG is in its liquid phase. This damage is costly and sometimes can be hard to replace to start with not mentioning the obstruction in the plant’s production and work.

According to the theory to calculate cold loss as shown before **Equation (24)** is to be used in general; however special conditions such as a pipe which has been laid outside of the plant when the wind has to be considered as well and **Equation (25)** has to be used. In order to be able to examine the temperature change of the flowing liquid on a given distance **Equation (14)** shall be used (the method is described in detail under **Chapter 3.1.3**). For being able to evaluate the pipe’s ability to avoid condensation and dew formation **Equation (26)** with **Table (6)** and **Figure (1)** should be used according to **Chapter 3.2.3**.

5.3 Material choices

Due to the extreme operating conditions coming hand in hand with LNG applications the material choices are enormously important. The standard, traditional materials in normal piping infrastructure usually materials that have known thermal and chemical properties and resistances at their own operating environment which ranges from room temperature towards the positive direction but they are not researched enough on sub – zero or cryogenic temperature ranges. This sometimes a direct consequence of the material’s physical attributes like the polyethylene (PE) pipes are known for their good low temperature performance in traditional piping infrastructure but they become brittle really fast in extreme conditions associated with LNG. This phenomenon present with some metallic materials as well, depending on their crystal structure some metals could become brittle in cryogenic temperatures (i.e. some steels) while others are perfect for operating under extremely low temperatures (i.e. copper).

The other issue with materials which is not necessarily condition dependent is the chemical resistance of the pipe. That means certain medium can react with certain chemicals therefore some materials are unavailable to use as a carrier pipe. With regards to LNG that generally impacts the thermoplastics however these materials are, as mentioned before, not suitable for carrying fluids sub – zero temperatures. And the materials that are able to transport the medium directly are not affected by any chemical issues. In Table VIII in the Appendix some of the most common thermoplastics and insulations materials are listed with their respective temperature tolerance and chemical resistance to natural gas.

From insulation point of view it is also indispensible to choose the right materials to be able to cope with the cryogenic temperature. Common insulation materials i.e. fiberglass or mineral wool are not suitable for operations in deep temperature range but other also common insulations are available like polyurethane foam which is one of the most common insulation type. However the design of the PUR foam matters because only those insulations could bear with the cryogenic conditions that are designed for that because PUR has a very varying temperature tolerance depending on the manufacturing. Apart from PUR foam there are other very useful materials to use but there are some issues with one of them which is the vermiculite. This material has a very wide temperature tolerance making it able to use in LNG applications but the issue with this material that it has been associated with asbestos and therefore proves to be dangerous material. However in LNG plants it still might be applicable because there might be parts of the plant where it would not pose health and safety danger on the workers. Other materials and their respective temperature tolerance can be further investigated with Table VIII in the Appendix.

5.4 Conclusion

As predictions indicate LNG use could rise in the near future based on the versatile applications and the demand rise of natural gas. Because it is an emerging market and technologically quite complicated the cost – intensiveness might turn out as a limiting factor in the future unless already ongoing development projects are able to find solution for the present issues with the applications. As per the calculation models for pre – insulated pipes stand as a generally wide spread and accepted way to evaluate thermodynamic properties of the infrastructure. Interesting and valuable data can be gained using the calculation method described, including inverse heat – loss ("cold loss") and the ability to able to see the temperature change of the LNG in the pipe on a given distance and under given conditions (such as the ambient temperature), one of the most important data can also be calculated which is the minimum insulation thickness to prevent structural failure due to dew formation. With this model thermodynamic design properties, i.e. insulation thickness and best insulation material, can be calculated for LNG applications effectively provided the necessary data is available (i.e. temperature values, diameter and/or thickness values, etc.).

In my opinion the greatest future challenge in LNG utilization would be the capital intensity associated with the infrastructure for LNG plants. The benefit of using traditional pre – insulated piping solutions would definitely be the cost reduction of the LNG constructions which could make it available for even more wide spread use of the technology. Also regarding the environmental and sustainability point of view the technology of liquefaction could become an interesting and high potential solution as a sustainable transportation fuel combined with biogas production. This solution would also solve issues regarding municipal waste management in a sustainable way.

6 Appendix

6.1 Appendix A – Equation list

$$q_{\mathrm{l}} = \frac{\theta_{\mathrm{si}} - \theta_{\mathrm{se}}}{R'_{\mathrm{l}}} \tag{1}$$

$$R'_{\mathrm{l}} = \frac{1}{2\pi}\sum_{j=1}^{n}\left(\frac{1}{\lambda_j}\ln\frac{D_{\mathrm{e}j}}{D_{\mathrm{i}j}}\right) \tag{2}$$

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{i}} - \theta_{\mathrm{sE}}}{R'_{\mathrm{l}} + R_{\mathrm{E}}} \tag{3}$$

$$R_{\mathrm{E}} = \frac{1}{2\pi\lambda_{\mathrm{E}}}\cosh^{-1}\frac{2H_{\mathrm{E}}}{D_n} \tag{4}$$

$$H_{\mathrm{E}} = H + \frac{D_{\mathrm{e}}}{2} \tag{5}$$

$$D_n = 1.073 \times a \tag{6}$$

$$\theta_{\mathrm{int}} = \theta_{\mathrm{i}} - q_{\mathrm{l,E}} * R_{pipe} \tag{7}$$

$$\theta_{\mathrm{sE}} = \theta_{\mathrm{int}} - q_{\mathrm{l,E}} * R_{ins} \tag{8}$$

$$q_t = 4\pi\lambda_{PUR}h_s\left(\frac{T_1 + T_2}{2} - T_0\right) \tag{9}$$

$$h_s = \frac{1}{\ln\left(\frac{(r_1)^2}{2Dr_2}\right) - \ln\left(\frac{(r_1)^4}{(r_1)^4 - D^4}\right) - \frac{\left(\frac{r_2}{2D} + \frac{2r_2D^3}{(r_1)^4 - D^4}\right)^2}{1 + \left(\frac{r_2}{2D}\right)^2 - \left(\frac{2r_2(r_1)^2D}{(r_1)^4 - D^4}\right)^2}} \tag{10}$$

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{i}} - \theta_{\mathrm{sE}}}{R'_{\mathrm{l}} + R_{\mathrm{le}}} \tag{11}$$

$$R_{le} = \frac{1}{h_{se} * \pi * D_e} \tag{12}$$

$$h_{se} = \frac{8.1 * 10^{-3}}{D_e} + 3.14 * \sqrt{\frac{v}{D_e}} \tag{13}$$

$$h_{se} = 3.96 * \sqrt{\frac{v}{D_e}} \tag{14}$$

$$\left|\theta_{im} - \theta_f\right| \tag{15}$$

$$\theta_f = |\theta_{im} - \theta_a| * e^{-\alpha * l} \tag{16}$$

$$\alpha = \frac{U_{tl} * 3.6}{\dot{m} * c_p} \tag{17}$$

$$U_{tl} = U_l + \Delta U_{bl} \tag{18}$$

$$\Delta U_{bl} = \frac{1}{l} \tag{19}$$

$$U_l = \frac{1}{R_l + \frac{1}{h_{se} * \pi * D_e}} \tag{20}$$

$$h_{se} = 1.25 * \sqrt[4]{\frac{\Delta\theta}{D_e}} \tag{21}$$

$$h_{se} = 1.32 * \sqrt[4]{\frac{\Delta\theta}{D_e}} \tag{22}$$

$$t_{\mathrm{v}} = \frac{(\theta_{im} - \theta_a) m c_p \ln \frac{(\theta_{im} - \theta_a)}{(\theta_f - \theta_a)}}{\phi_{\mathrm{T}} * 3.6} \tag{23}$$

$$\phi_{\mathrm{T}} = U_{tl} * l(\theta_{im} - \theta_a) \tag{24}$$

$$t_{wp} = \frac{(\theta_{im} - \theta_a)\left(m_w c_{pw} + m_p c_{pp}\right) \ln \frac{(\theta_{im} - \theta_a)}{(\theta_f - \theta_a)}}{\phi_{\mathrm{T}} * 3.6} \tag{25}$$

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{sE}} - \theta_{\mathrm{i}}}{R_{\mathrm{l}}' + R_{\mathrm{E}}} \tag{26}$$

$$q_{\mathrm{l,E}} = \frac{\theta_{\mathrm{sE}} - \theta_{\mathrm{i}}}{R_{\mathrm{l}}' + R_{\mathrm{sE}}} \tag{27}$$

$$C' = \frac{2\lambda}{h_{se}} \left(\frac{|\theta_{im} - \theta_a|}{|\theta_{se} - \theta_a|} - 1 \right) \tag{28}$$

6.2 Appendix B – Tables

TABLE I

Carrier pipe dimensions (EN 253:2009)

Carrier pipe dimensions (Steel)	Outer Diameter [mm]	Min thickness [mm]	Inner Diameter [mm]
DN 15	21,3	2	17,3
DN 20	26,9	2	22,9
DN 25	33,7	2,3	29,1
DN 32	42,4	2,6	37,2

DN 40	48,3	2,6	43,1
DN 50	60,3	2,9	54,5
DN 65	76,1	2,9	70,3
DN 80	88,9	3,2	82,5
DN 100	114,3	3,6	107,1
DN 125	139,7	3,6	132,5
DN 150	168,3	4	160,3
DN 200	219,1	4,5	210,1
DN 250	273	5	263
DN 300	323,9	5,6	312,7
DN 350	355,6	5,6	344,4
DN 400	406,4	6,3	393,8
DN 450	457	6,3	444,4
DN 500	508	6,3	495,4
DN 600	610	7,1	595,8
DN 700	711	8	695
DN 800	813	8,8	795,4
DN 900	914	10	894
DN 1000	1016	11	994
DN 1200	1219	12,5	1194

TABLE II

PUR insulation dimensions (EN 253:2009)

PUR insulation dimensions	Outer Diameter [mm]	Inner Diameter [mm]	Min thickness [mm]
DN 15	90	21,3	34,35
DN 20	110	26,9	41,55
DN 25	125	33,7	45,65
DN 32	140	42,4	48,8
DN 40	160	48,3	55,85
DN 50	180	60,3	59,85
DN 65	200	76,1	61,95
DN 80	225	88,9	68,05
DN 100	250	114,3	67,85
DN 125	280	139,7	70,15
DN 150	315	168,3	73,35
DN 200	355	219,1	67,95
DN 250	400	273	63,5
DN 300	450	323,9	63,05
DN 350	500	355,6	72,2
DN 400	560	406,4	76,8

DN 450	630	457	86,5
DN 500	710	508	101
DN 600	800	610	95
DN 700	900	711	94,5
DN 800	1000	813	93,5
DN 900	1100	914	93
DN 1000	1200	1016	92
DN 1200	1400	1219	90,5

TABLE III

Casing pipe dimensions (EN 253:2009)

Casing dimensions (PE)	Outer Diameter [mm]	Min thickness [mm]	Inner Diameter [mm]
DN 15	90	3	84
DN 20	110	3	104
DN 25	125	3	119
DN 32	140	3	134
DN 40	160	3	154
DN 50	180	3	174
DN 65	200	3,2	193,6
DN 80	225	3,4	218,2
DN 100	250	3,6	242,8
DN 125	280	3,9	272,2
DN 150	315	4,1	306,8
DN 200	355	4,5	346
DN 250	400	4,8	390,4
DN 300	450	5,2	439,6
DN 350	500	5,6	488,8
DN 400	560	6	548
DN 450	630	6,6	616,8
DN 500	710	7,2	695,6
DN 600	800	7,9	784,2
DN 700	900	8,7	882,6
DN 800	1000	9,4	981,2
DN 900	1100	10,2	1079,6
DN 1000	1200	11	1178
DN 1200	1400	12,5	1375

TABLE IV

Distance between carrier pipes (EN 15698-1:2009)

Pipe Design	Distance Between carrier pipes [mm]
DN 15	19
DN 20	19
DN 25	19
DN 32	19
DN 40	19
DN 50	20
DN 65	20
DN 80	25
DN 100	25
DN 125	30
DN 150	40
DN 200	45
DN 250	45

TABLE V

Material properties

Materials	λ[W/mK]
HDPE	0,42
LDPE	0,32
XLPE	0,38
Steel	45
Stainless Steel	16
Glassfiber	0,2
PP	0,22
PVC	0,18
PB	0,22
Aluminium	218
Copper	390
PUR	0,025
PET foam	0,03
EVOH solid	0,341
Mineral Wool	0,07
Glasswool	0,04

TABLE VI

Thermal conductivities of common soil types

Soil Type	lambda λ
Sand (dry)	0,15
Sand (moist)	0,25
Soil (clay)	1,1
Soil (organic matter)	0,2
Snow	0,1

TABLE VII

Allowed temperature differences [K] between the pipe surface and ambient air for different relative humidity

Ambient air temperature [°C]	Relative air humidity [%]													
	30	35	40	45	50	55	60	65	70	75	80	85	90	95
-20	-	10,4	9,1	8	6,9	6	5,2	4,5	3,7	2,9	2,3	1,7	1,1	0,5
-15	12,3	10,8	9,6	8,3	7,3	6,4	5,4	4,6	3,8	3,1	2,5	1,8	1,2	0,6
-10	12,9	11,3	9,9	8,7	7,6	6,6	5,7	4,8	3,9	3,2	2,5	1,8	1,2	0,6
-5	13,4	11,7	10,3	9	7,9	6,8	5,8	5	4,1	3,3	2,6	1,9	1,2	0,6
0	13,9	12,2	10,7	9,3	8,1	7,1	6	5,1	4,2	3,5	2,7	1,9	1,3	0,7
2	14,3	12,6	11	9,7	8,5	7,4	6,4	5,4	4,6	3,8	3	2,2	1,5	0,7
4	14,7	13	11,4	10,1	8,9	7,7	6,7	5,8	4,9	4	3,1	2,3	1,5	0,7
6	15,1	13,4	11,8	10,4	9,2	8,1	7	6,1	5,1	4,1	3,2	2,3	1,5	0,7
8	15,6	138,8	12,2	10,8	9,6	8,4	7,3	6,2	5,1	4,2	3,2	2,3	1,5	0,8
10	16	14,2	12,6	11,2	10	8,6	7,4	6,3	5,2	4,2	3,3	2,4	1,6	0,8
12	16,5	14,6	13	11,6	10,1	8,8	7,5	6,3	5,3	4,3	3,3	2,4	1,6	0,8
14	16,9	15,1	13,4	11,7	10,3	8,9	7,6	6,5	5,4	4,3	3,4	2,5	1,6	0,8
16	17,4	15,5	13,6	11,9	10,4	9	7,8	6,6	5,4	4,4	3,5	2,5	1,7	0,8
18	17,8	15,7	13,8	12,1	10,6	9,2	7,9	6,7	5,6	4,5	3,5	2,6	1,7	0,8
20	18,1	15,9	14	12,3	10,7	9,3	8	6,8	5,6	4,6	3,6	2,6	1,7	0,8
22	18,4	16,1	14,2	12,5	10,9	9,5	8,1	6,9	5,7	4,7	3,6	2,6	1,7	0,8
24	18,6	16,4	14,4	12,6	11,1	9,6	8,2	7	5,8	4,7	3,7	2,7	1,8	0,8
26	18,9	16,6	14,7	12,8	11,2	9,7	8,4	7,1	5,9	4,8	3,7	2,7	1,8	0,9
28	19,2	16,9	14,9	13	11,4	9,9	8,5	7,2	6	4,9	3,8	2,8	1,8	0,9
30	19,5	17,1	15,1	13,2	11,6	10,1	8,6	7,3	6,1	5	3,8	2,8	1,8	0,9
35	20,2	17,7	15,7	13,7	12	10,4	9	7,6	6,3	5,1	4	2,9	1,9	0,9
40	20,9	18,4	16,1	14,2	12,4	10,8	9,3	7,9	6,5	5,3	4,1	3	2	1
45	21,6	19	16,7	14,7	12,8	11,2	9,6	8,1	6,8	5,5	4,3	3,1	2,1	1
50	22,3	19,7	17,3	15,2	13,3	11,6	9,9	8,4	7	5,7	4,4	3,2	2,1	1

TABLE VIII

Temperature tolerance and chemical resistance of some common thermoplastics and insulations

Materials	Abbreviation	Structural function	Temperature resistance		Chemical resistance
High density polyethylene	HDPE	Carrier pipe, Casing pipe	-35	50	Limited
Low density polyethylene	LDPE	Carrier pipe, Casing pipe	-35	50	Limited
Cross - linked polyethylene	PEX	Carrier pipe, Casing pipe	-45	90	Up to 140 °C
Polypropylene	PP	Carrier pipe, Casing pipe	-20	80	Limited
Polyvinyl Chloride	PVC	Carrier pipe, Casing pipe	-30	60	Up to 140 °C
Polybutylane	PB	Carrier pipe, Casing pipe	-17	70	Limited
Polyurethane	PUR	Insulation	-198	140	-
Glassfiber	-	Insulation	-30	540	-
Mineral wool	-	Insulation	0	750	-
Glasswool	-	Insulation	0	250	-
Cellular Glass	-	Insulation	-260	480	-
Polyisocyanurate	Polyiso	Insulation	-180	150	-

6.3 Appendix C – Figures

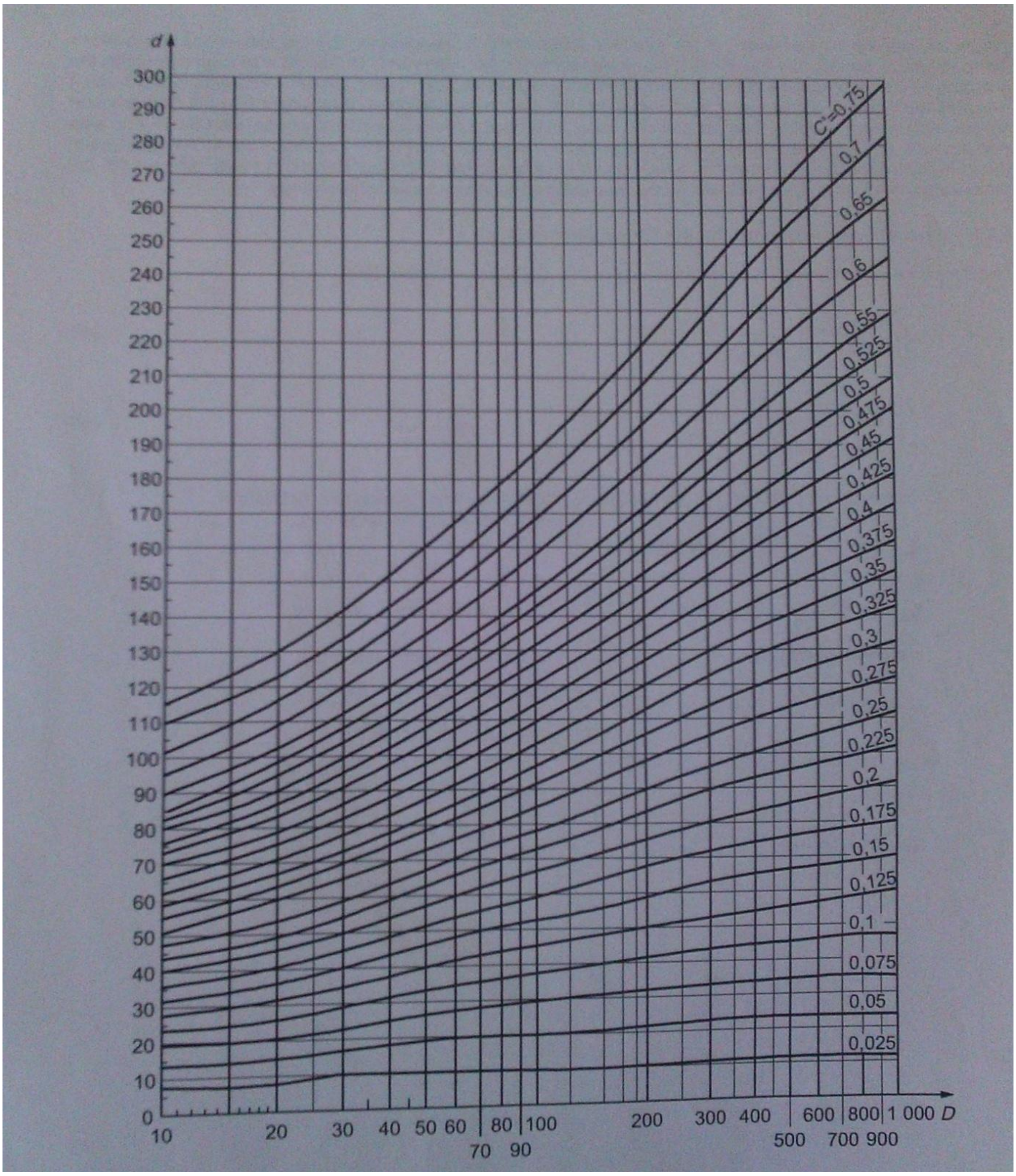

Fig. 1 **Determination of insulating layer thickness for a pipe at a given heat flux density or for a set surface temperature**

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