POLITENICO DI TORINO

MSc in Energy and Nuclear Engineering – Renewable Energy Systems

ENERGY NETWORKS COURSE

DESIGN OF A GAS NETWORK SYSTEM

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SUMMARY

INTRODUCTION

The objective of this project is the design and the analysis of a municipal gas network, 4^{th} species.
The steps to follow are:
1) Design of a natural gas network
2) Fluid dynamic analysis of the network
3) Fluid dynamic analysis of the network under distributed injection of renewable gas

The natural gas is delivered in the pipelines and there is a hierarchy about them in terms of pressure. In Italy the pipelines are regulated by DM 24/11/1984 and its subsequent modifications (DM 16/04/2008 + DM 17/04/2008).
Rules for fire protection in transportation, delivery, storage and usage of natural gas, with density lower or equal to 0,8 (with respect to air).
The Italian main features are:

- >32,600 km of transport pipelines
- 72.8 bcm of Natural Gas injected (yearly)
- 11 compression stations
- 8 entry points: 5 pipeline interconnections and 3 LNG regasification terminals

The figure 1 shows a part of the Italian gas network

Figure 1 – National network of S.G.I.

NETWORK DESIGN

The design gas network is based in Turin. In order to have a shape of the network as faithful as possible with respect to the real networks and knowing that usually the pipelines of the network have to follow the shape of the streets, we have decided to shape the network taking into account a real map of the center of Turin, the same configuration has been used for the district heating network

In the figures 2 there is represented the tree shaped network, in which the nodes are numbered starting to the ReMi station (node 1), the CHP plant (node 14-a) and the buildings.

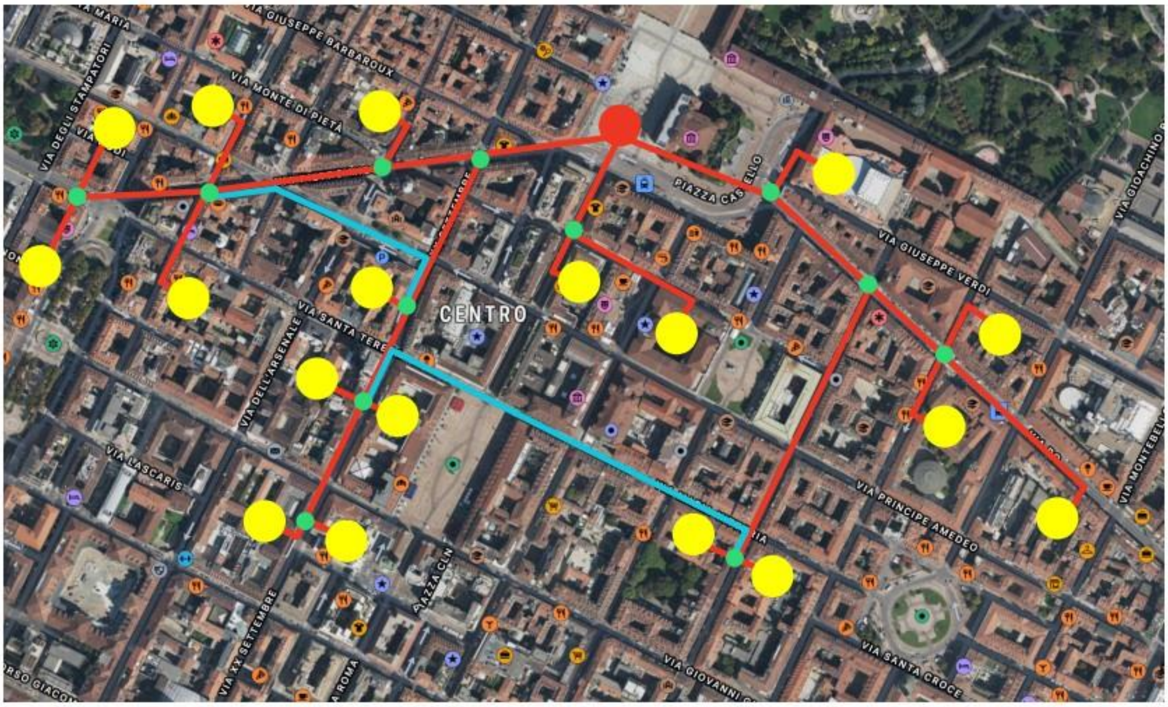

Figure 2 – Gas network pipelines

We have assumed to place the ReMi station at the center of "Piazza Castello", from this point the network follows the topology of the city. Considering the tree-shaped network, there are three main branches starting from the plant, then we have added additional branches to create two loops.

A more schematic representation of the network is shown in figure 3-4. The red dot is the ReMi station, the yellow dots are the users, and the green ones are the nodes of the network.
Additionally to the buildings, we consider a further consumption node that is represented by the thermal plant that is needed to provide heat to the DHS, so we installed a co-generation system.
This power plant provides both thermal power, for heating purposes, and electricity.

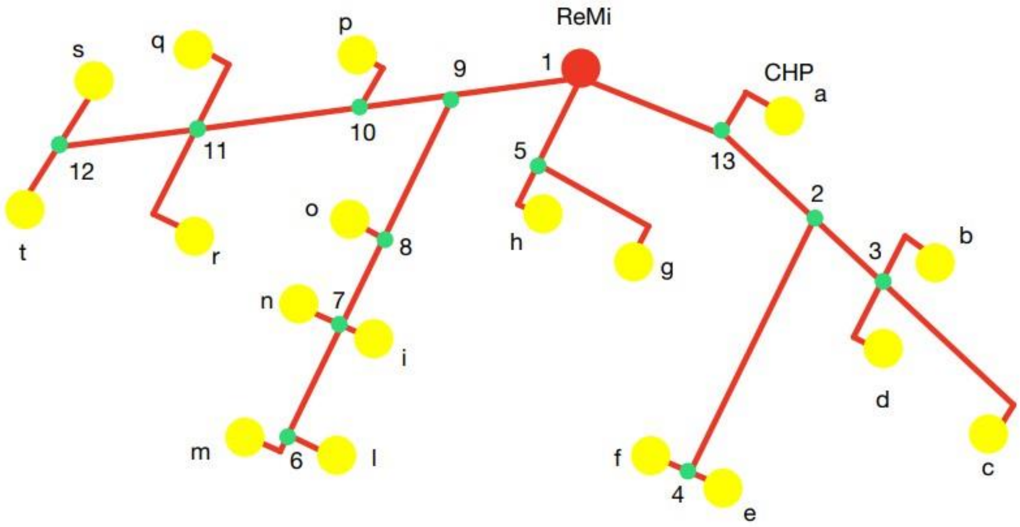

Figure 3 – Scheme of gas network

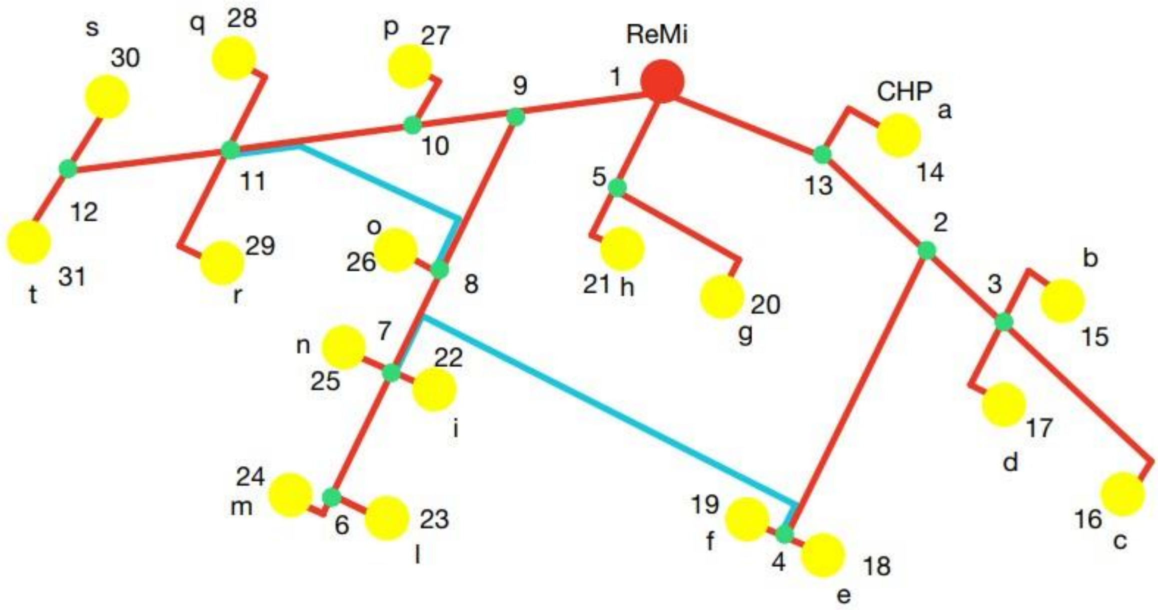

Figure 4 – Scheme of gas network with loops

In this configuration we have 32 branches and 31 nodes (17 buildings).
The branches lengths are between 300 m and 3000 m.
The buildings have different volumes between 30.000 m^3 and 250.000 m^3.
We consider the same external design temperature of the DH project.
We choose one of the typical gasses among the Italian ones, the natural gas coming from North Europe through the entry point in Passo Gries.

Table 1 – Natural gas mixture composition

	Molar Fraction [%]	Viscosity [Pa*s]
Methane	92,043	1,10E-05
Ethane	4,647	9,50E-06
Propane	0,804	1,40E-05
Iso Butane	0,144	7,00E-06
Normal Butane	0,125	7,00E-06
Iso Pentane	0,039	2,20E-04
Normal Pentane	0,024	2,20E-04
Hexanes	0,04	3,30E-04
Nitrogen	0,911	1,60E-05
Carbon dioxide	1,195	1,40E-05
Helium	0,028	1,90E-05
Oxygen	-	-

The Natural gas characteristics are in table 2:

Table 2 – Natural gas properties

HHV [kWh/m3]	10,854
LHV [kWh/m3]	9,801
WI [kWh/m3]	13,935
Density [kg/m3]	0,74341
Relative density	0,60666
Compressibility factor (Z)	0,99767
Molecular weight [kg/kmol]	17,54

For what concern the CHP plant we assumed the amount of power equal to 8 MW, divided into 2,455 MW needed for the district heating and the remaining 5,5 MW of electricity. With η = 60% the power needed at the input of the CHP plant is 8 MW.
Considering the lower heating value of our natural gas we can calculate the amount of gas needed at the inlet of node 14 in the full load conditions, that is 1362,07 $[m^3/h]$.

Table 3 - Gas consumption and amount of electrical power

DHpower [MW]	2,455
η production	0,6
CHP net power [MW]	8
electric power [MW]	5,5
CHP power [MW]	13,3
Gas needed [m3/h]	1362,07

PIPELINE SIZING AND FERGUSSON EQUATION

The Fergusson equation correlates the square of outlet and inlet pressures with fluid resistance R_f and the volumetric flow rate Q

$$p_{in}^2 - p_{out}^2 = R_f |Q| Q$$

Where $R_f = \frac{16\lambda\rho^2 c^2 l}{\pi^2 D^5}$.
This equation expresses the momentum equation, basing on the assumptions of isothermal gas flow rate (considered at the ground temperature of 15°C), steady-state condition (inertial term is neglected) and negligible convective term.
By this equation we can state other semi-empirical correlations which are more frequently used for modeling and sizing of the gas network: we consider the Renouard correlation for high-medium pressure case:

$$p_{in}^2 - p_{out}^2 = R_{R_{MP}} Q^{1.82} L$$

Where $R_{R_{MP}} = 5.20e-7 \frac{\rho_n}{\rho_{air}} \frac{1}{D^{4.82}}$is the fluid-dynamic resistance with ρ_n is the gas density at standard condition, L is the equivalent pipe length considering effective pipe length and pressure losses and D is the pipe diameter. The unit of measurement of pressure in the formula is expressed in $\frac{kg}{cm^2}$.
The unknown is the internal diameter of the pipes, and its evaluation is performed by an iterative calculation.
The equivalent length is evaluated by summing the effective pipe length with the pressure losses, evaluated as function of pipe angles or roughness.
The formula of internal diameter in a tree-shaped network is the following:

$$D = 2\sqrt{\frac{Q}{\pi v} \frac{\rho_n}{\rho_{NGactual}}}$$

It is applied for each branch where the velocity v is set at 25 m/s: this is the limit value of the velocity and it imposes the limit situation. The volumetric flow rates are related to the density of natural gas in standard conditions, by imposing the mass conservation principle at node 1. It is set to 0.1 $\frac{m^3}{s}$ at loops.
The main points that must be respected are:

- In order to give solid mechanical structure to the network the same diameter is adopted for all branches belonging to the main trunk. This is effective in case of future connections and expansion of the line
- The loops require velocity of 1 m/s at first step and their diameter is equal to the biggest one among the neighbor pipes
- The diameters must respect the convention of decreasing by moving from the station to the users

The downstream approach is used to make the evaluation of the pressure: starting from the ReMi station with a pressure of 6 bar_g, the pressures are evaluated by considering in the Renouard the pressure exiting from the branch the real unknown

$$P_{out} = \sqrt{P_{in} - R_{R_{MP}} Q^{1.82} L}$$

The minimum value of the pressure is 1.5 bar_g. All the pressure values are supposed to decrease moving from the ReMi station to the users. In the case of pressure values under the limit, the diameter must be modified, causing a velocity decrease in the pipe considered. Once the two pressure values are calculated, the pressure drop is evaluated at each branch: this is a good marker for the presence of bottlenecks and it helps to understand if the diameter sizing was correct. The calculation of the pressures is made by means of the theoretical diameter. In the real case we have to consider that real diameters have fixed dimensions, so we have to choose a diameter:

$$D_N \geq 0{,}95\ D_{teo}$$

If we want to make a comparison between district heating system and gas network, we are not considering in this case the relation between velocity and pumping costs. The gas network is a pressurized system at distribution level: there is no need for pumping. The pressure difference is due to the gas spilling.
In figure 5 are plotted the values of diagrams.

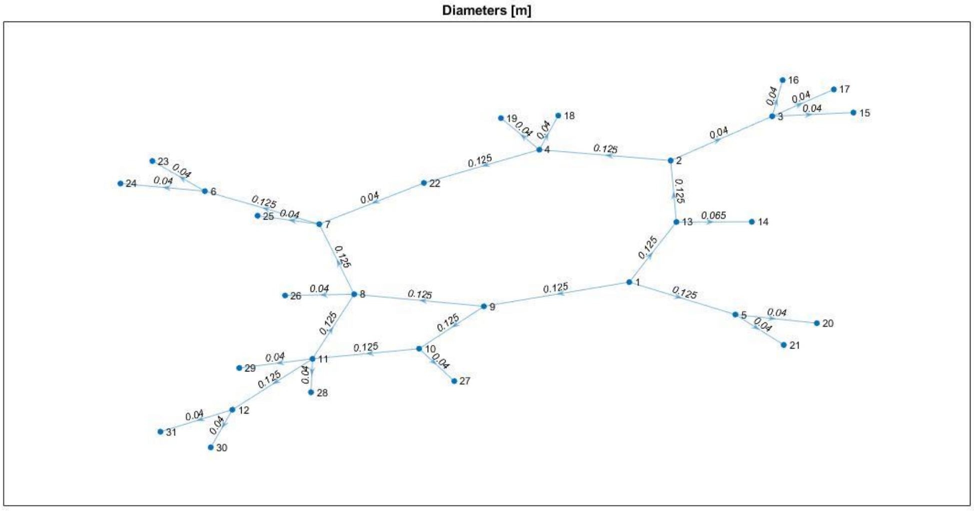

Figure 5 – Values of diameters

The network is a tree-shaped one. In order to calculate the pressure at each node and the mass flow rate at each branch into the loop network, the SIMPLE and the fixed-point algorithms have been used, in similar way for the district heating case. The initial value requested to start the iterative calculation are guessed values.

FLUID-DYNAMIC SIMULATION OF A GAS NETWORK

In order to make a fluid-dynamic analysis of a gas network we have to analyze the conservation of mass and momentum equations. Here they are written for a horizontal pipe:

$$\frac{\partial \rho}{\partial t} + \frac{\partial (\rho v)}{\partial x} = 0$$

$$\frac{\partial (\rho v)}{\partial t} + \frac{\partial (\rho v^2)}{\partial x} + \frac{\partial p}{\partial x} + \frac{\lambda \rho v |v|}{2D} = 0$$

In steady state conditions, the derivatives with respect to the time are null.
For incompressible fluids the situation is simpler: since the density ρ cannot change, all the derivatives of ρ are null and the equations have less terms, this happens in the simulation of the district heating case.
In the gas network case, we are working with a compressible fluid, therefore the density depends on the temperature and pressure of the fluid at each node, taking into account the following equation:

$$\rho = f(T, p)$$

$$\frac{p}{\rho} = Z \frac{R_0}{MM} T = c^2$$

Where c is the isothermal speed of sound and Z is the compressibility factor.
The compressibility factor is equal to 1 when we work with an ideal gas that is at low/atmospheric pressure. Since our 4^{th} specie network has pressures between 5 and 1.5 bar_g, we cannot use the ideal gas approximation, so the value of Z will be lower than 1.
There are various ways to determine Z, in this case the PAPAY formula, an empirical formulation, is used and it is implemented in the MATLAB code:

$$Z = f(T, p, [y])$$

At this point we can write the conservation of mass and momentum equations in matrix form, in this way they are easier to implement in the MATLAB code:

$$XM + M_{EXT} = 0$$

$$X'\mathcal{P} = R_c(M) \cdot M$$

Where $\mathcal{P}$ represents the pressures elevated at the second power and R_c is:

$$R_c = \frac{\lambda \frac{L}{D} c^2}{A^2} |\dot{m}|$$

Where L is the length of the pipe, D is its diameter, c is, as already said, the isothermal speed of sound, A is the cross-section area of the pipes and λ is the friction factor.
In order to properly evaluate the friction factor λ it is important to know if the flow is laminar or turbulent, for this reason the Reynolds number is calculated:

$$Re = \frac{\rho v D}{\mu}$$

The Reynolds number depends on the density, the velocity and the viscosity of the fluid as well as the diameter of the pipe. After this calculation we can define three cases:

1. $Re < 2000$ → Laminar Flow
2. $2000 < Re < 3400$ → Transition Region
3. $Re > 3400$ → Turbulent Flow

In the first case λ is simply computed as:

$$\lambda = \frac{64}{Re}$$

In the transition region, the Cheng equation in the explicit form has been implemented, instead in the third region the Hofer correlation has been used. A function is implemented in MATLAB in order to perform the calculation of the friction factor in the various cases.

For the Reynolds number, the calculation of the viscosity of the mixture has to be performed, it is the average of the dynamic viscosities of the single components weighted over the square roots of their molecular masses. It is important to say that the viscosity μ does not depend on the pressure but it depends on the temperature, fortunately we are in an isothermal case. The data for the computation of μ are shown in the table 1.
In the following figures, the obtained results are shown and commented.

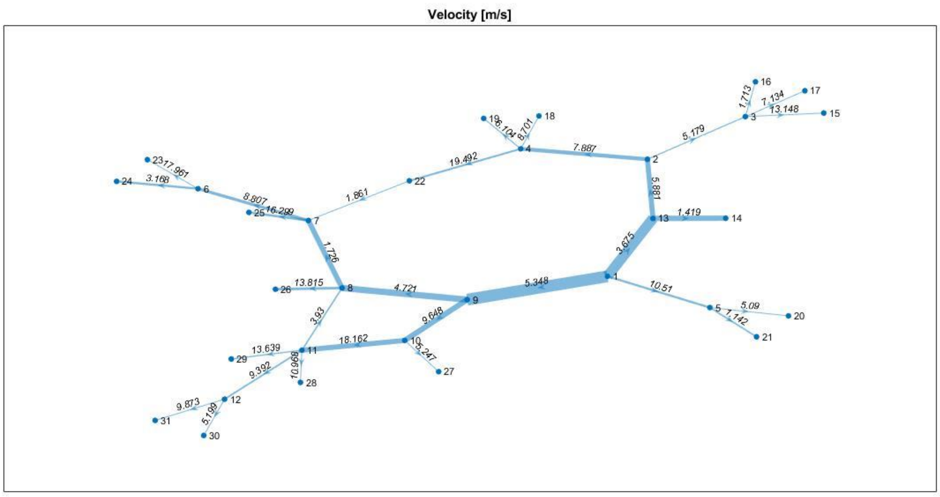

Figure 6 - Velocities

The maximum velocity is a little less than 20 m/s. Since the limit for this kind of network can be up to 25 m/s, we have decided to size the plant for lower velocities to take into account for the possible future expansion of the network.

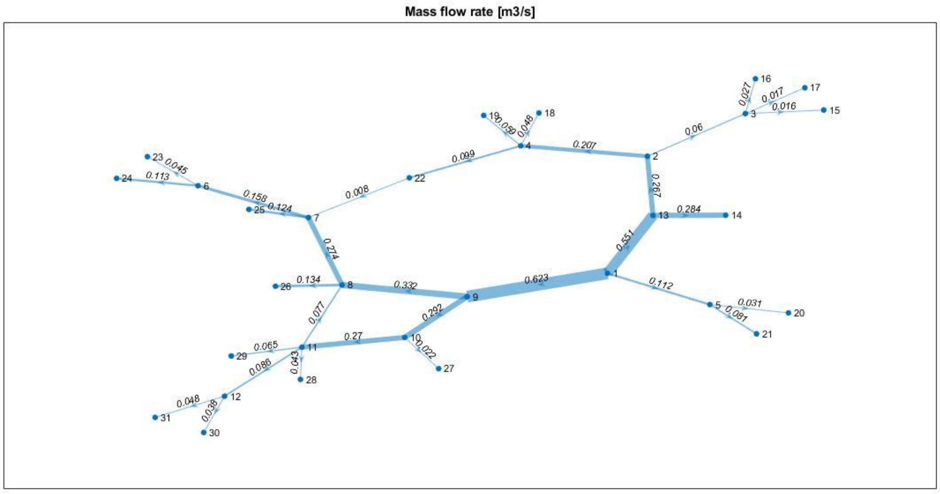

Figure 7 - Mass Flow Rates

The mass flow rates are higher near to the ReMi station and decrease in the peripheral branches of the network. This is because the mass flow rate depends on the diameter of the pipe that is maximum in the main branches of the network.

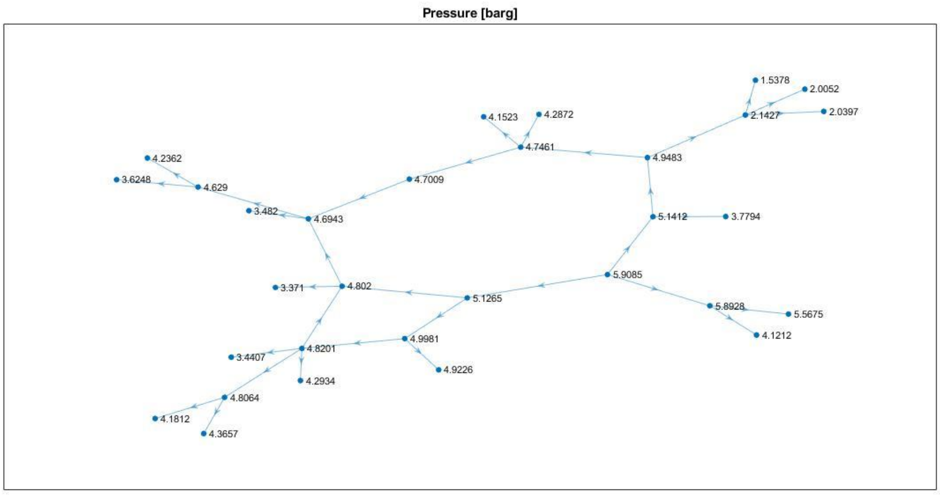

Figure 8 - Pressures

Like for the mass flow rates, it is possible to observe that the highest pressure is in node 1, since it is equal to 5.91 bar_g it slightly exceeds the maximum pressure allowed for a 4th species network. Moving away from the first node that represents the ReMi station, the pressure starts to diminish proportionally to the equivalent length of the pipelines, until a minimum of 1.54 bar_g in node 16.

MULTI-COMPONENT MODELLING

We decide to inject in node 9 the blending of natural gas with hydrogen. The particular a quantity of hydrogen has been decided with respect to the value of relative density, higher heating value and Wobbe Index. In particular these values have to remain in certain boundaries according to the Italian regulation DM 21/11/1984, if these boundaries are exceeded the blending can not be injected in the network. The procedure to determine the quantity of hydrogen is shown in the table 6.

Table 4 – Hydrogen properties

H2	
Relative density [-]	0,06693877551
Molecular Weight [kg/kmol]	2,016
Density [kg/kmol]	0,082
HHV [kWh/m3]	3,242
LHV [kWh/m3]	2,743

Table 5 – Hydrogen blending in the network

	Molar Fraction [%]	Molar Fraction [%]	Molar Fraction [%]
Methane	92,043	87,44085	82,8387
Ethane	4,647	4,41465	4,1823
Propane	0,804	0,7638	0,7236
Iso Butane	0,144	0,1368	0,1296
Normal Butane	0,125	0,11875	0,1125
Iso Pentane	0,039	0,03705	0,0351
Normal Pentane	0,024	0,0228	0,0216
Hexanes	0,04	0,038	0,036
Nitrogen	0,911	0,86545	0,8199
Carbon dioxide	1,195	1,13525	1,0755
Helium	0,028	0,0266	0,0252
Oxygen	0	0	0
Hydrogen	0	5	10

Table 6 – Blending operation

	0% of H2	5% of H2	10% of H2
HHV [kWh/m3]	10,854	10,4734	10,0928
LHV [kWh/m3]	9,801	9,4481	9,0952
Density [kg/m3]	0,74341	0,7103	0,6773
Molecular weight [kg/kmol]	17,54	16,7638	15,9876
Wobbe Index [kWh/m3]	13,935	13,754	13,574
Compressibility factor Z	0,99767		
Air Density [kg/m3]	1,225	1,225	1,225
Wobbe Index [MJ/m3]	50,166	49,5136854	48,8654175
Relative density [-]	0,6069	0,5799	0,5529
HHV [MJ/m3]	39,08009662	37,70424	36,33408

As shown in table 6 the blending operation consist in increasing the percentage of the hydrogen in the mixture without overcome the constraint of the three limits. For a value of 10% of hydrogen the relative density reaches its limit. This is because hydrogen has a very low density with respect to the natural gas and we reach the minimum of the relative density that our pipe can bear.

CONCLUSION

In conclusion we can say that the parameters of pressure, mass flow rate and pipe diameters are strictly correlated as shown in the Fergusson equation. With respect to the case of district heating we now have to take into account the compressible fluid properties, so in this case density of the fluid change with temperature and pressure and the computation is more complex.
Hydrogen blending in the network can help the decarbonization of the energy sector, however we can inject just a little amount of hydrogen in the network and we also have to take into account that the energy density of hydrogen is about one third of the one of natural gas, so we are decarbonizing just about the 3% of the total energy produced.

REFERENCE

https://www.gasdottitalia.it/it/content/descrizione-del-sistema-di-trasporto