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District heating network design and analysis

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Abstract

The drive for achieving high values of fuel utilization factor, in the last years, has led to an increasing attention to combined heat and power (CHP) plants.

In this scenario, the district heating allows to achieve high conversion efficiencies by centralizing in few large power plants the need of thermal energy in household sector. The power plants that feed the District Heating Networks (DHN) usually work by combined heat and power set-up.

District Heating Networks have found a large development in the last decades. The main advantage of DHNs is the reduction of pollutant and thermal emissions in the city area. Further, the large use of DHNs increases the safety, due to the absence of combustion systems at the final users of thermal energy. For the same reason also the transportation of fuel in the city area can be drastically reduced by the use of DHNs.

On the basis of the previous observations, in this study a new software for the DHNs design and analysis is described and validated. This software, which has been developed by University of Bologna, is based on the Todini-Pilati algorithm generalized by the use of Darcy-Weisbach equation.

More in details, in this paper the main physical-mathematical models adopted in the realized software, called Ca.R.Di.F., and its validation are described.

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Keywords: District Heating Network; software development; Todini-Pilati algorithm;

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1. Introduction

In the last few years the Combined Heat and Power (CHP) production has shown a rapid growth, particularly with the aim of increasing the values of the fuel utilization factor. The final users of heat and power may be various.

In the civil sector, the direct production of thermal energy for hot water and space heating, can be replaced with the district heating. In this case, the centralized production of heat and the consequent distribution of hot water (usually ranging from 90 to 130°C [1]) is realized. District Heating Networks (DHNs) enable to obtain several advantages, with regard to either practical or environmental and safety aspects. First of all, the use of DHNs allows to drastically reduce both pollutant and thermal emissions at the city area. Moreover DHNs enable to remove the combustion systems at the final users of thermal energy, increasing therefore the safety conditions and eliminating the transportation of fuel in the city area. At last the absence of the boiler also allows reducing the occupied space and the maintenance at the final users.

Nowadays, in Italy DHNs are installed in 104 cities for a total of 133 systems and a connected volumetry of 260'000'000 m³ (approximately 1'084'600 equivalent apartments) [2]. Figure 1 shows the increasing trend of connected DHN volumetry since 1972 to 2011.

The thermal energy provided is about 7'416 GWh, combined with 5'201 GWh of electrical energy. In this scenario, District Heating (DH) allow to save 404'922 toe and avoid about 1'323'601 ton of CO₂ emissions [2].

However, at present, in Italy only the 4% of thermal energy need for hot water and space heating is provided via district heating, whereas, as shown in Figure 2, this percentage is higher in the rest of Europe.

Because of the increasing diffusion of DH, a new software for DHNs design and analysis has been developed. On the following of this study the main physical-mathematical model of the software will be presented and discussed. Further, comparing the results obtained applying that software and the commercial software Termis to an existing network, the developed software will be validated.

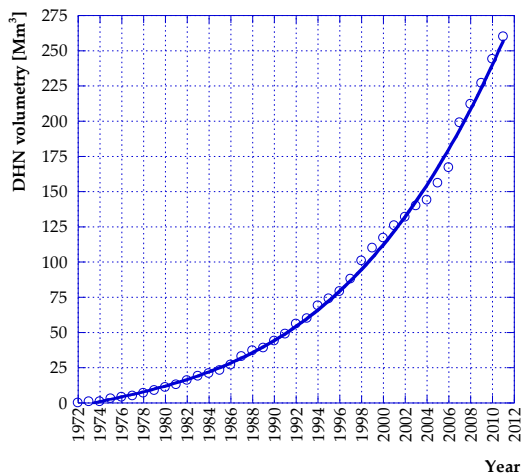


Fig. 1. trend of DHN volumetry in Italy between 1972 and 2012 [2]

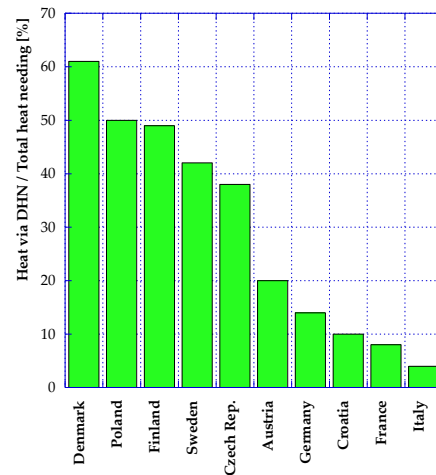


Fig. 2 percentage of district heating in Europe at 2011 [2]

Nomenclature

CHP	combined heat and power
D	hydraulic diameter
dE	energy balance residual
DH	district heating
DHN	district heating network
dq	mass flow rate balance residual
f	Darcy friction factor
f_0	Moody friction factor
H	liquid energy content
IN	inlet
L	length of the pipe
m	iteration m
MTR	mean total residual
NN	number of nodes
NP	number of pipes
OUT	outlet
q, Q	mass flow rate
Re	Reynolds number
v	fluid mean velocity
β	concentrated pressure losses coeff.
ΔH	pressure loss
ε	roughness height
ρ	density

2. Todini-Pilati algorithm

The realized calculation software is based on the Todini – Pilati [3, 4] algorithm for what concerns the resolution of the network. Others methods were defined by Wood and Charles [5], by Epp and Fowler [6] and later by Kesavan and Chandrashekar [7] or by Martin and Peters [8] and by Shamir and Howard [9]. The choice of Todini – Pilati algorithm has been done considering the fast convergence and the robustness of this resolution method [3].

Generally speaking, an hydraulic network can be represented considering a given numbers of nodes (NN) and of pipes (NP).

As example, in Figure 3 a portion of a generic hydraulic network is presented; in this case $NN=6$ and $NP=5$.

With reference to Figure 3, it can be observed that a node can be (i) a mixer (see node 2 in Figure 3, in which the sum of the inlet mass flow rate is equal to the sum of the outlet mass flow rate), (ii) an utility (see node 3 or 4 in Figure 3 in which the difference between the inlet and outlet mass flow rate to the node is equal to the required flow, q_3 of q_4 in Figure 3), or (iii) a source (which introduces the flow into the network).

For each pipe (p_{ij}) of the networks, the energy balance, being i and j respectively the upstream and the downstream nodes, can be written as:

$$\Delta H_{p_{ij}} - (H_i - H_j) = 0 \quad (1)$$

where $\Delta H_{p_{ij}}$ represents the pressure losses through the pipe, while H_i and H_j are the energy content of the liquid respectively in node i and j .

Obviously, $\Delta H_{p_{ij}}$ can be expressed as the sum of the distributed and concentrated pressure losses. The distributed pressure losses are calculated with the Darcy-Weisbach equation:

$$\Delta H_{dis} = f \frac{L}{D} \rho \frac{v^2}{2} \quad (2)$$

where: f is the Darcy friction factor, L is the length of the pipe, D is the diameter of the pipe, ρ is the density of the fluid, and v is the mean velocity of the fluid. The friction factor f can be calculated by the use of the expression, in implicit form, proposed by Colebrook and White:

$$f = \left[-2 \cdot \log \left(\frac{2.51}{\text{Re} \cdot f^{1/2}} + \frac{1}{3.71} \frac{\varepsilon}{D} \right) \right]^{-2} \quad (3)$$

being ε the roughness height, D the hydraulic diameter, (which is equal to the inside diameter for circular conduits) and Re the Reynolds number. The previous relationship of the friction factor can be turned into an explicit form by substituting f with f_0 in the second member; f_0 can be calculated according to Moody as:

$$f = \left[-2 \cdot \log \left(\frac{2.51}{\text{Re} \cdot f_0^{1/2}} + \frac{1}{3.71} \frac{\varepsilon}{D} \right) \right]^{-2} \quad (4)$$

$$f_0 = 0.0055 \cdot \left[1 + \left(20000 \frac{\varepsilon}{D} + \frac{10^6}{\text{Re}} \right)^{1/3} \right] \quad (5)$$

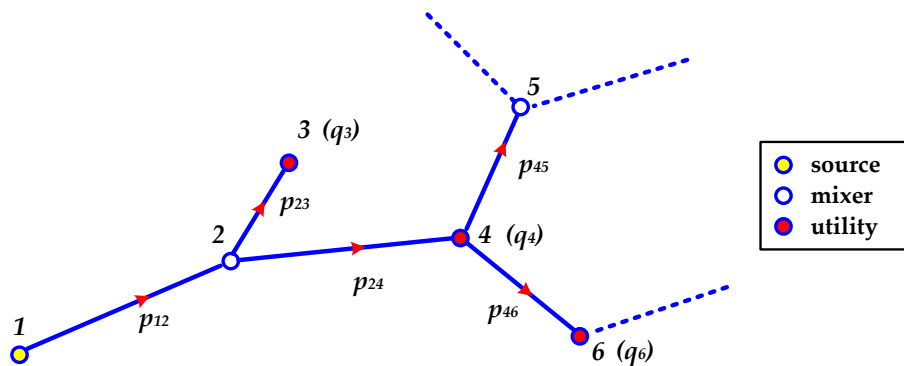


Fig. 3. Example of a portion of a DHN

The presented approach with regard to the calculation of pressure drops represents an improvement compared to that proposed in other software that use simplified expression of f to limit the computational load.

For the concentrated pressure losses the equation to consider is:

$$\Delta H_{con} = \beta \cdot \rho \frac{v^2}{2} \quad (6)$$

being β is the coefficient of the concentrated pressure drops. The value of β can be found in literature as function of the considered geometry.

Further, for each node of the considered network the balance of the mass flow rate can be written as:

$$\sum_{IN} Q_{IN} - \sum_{OUT} Q_{OUT} - \sum_U q_U = 0 \tag{7}$$

In Eq. 7 $\sum_{IN} Q_{IN}$ and $\sum_{OUT} Q_{OUT}$ represent respectively the sum of the mass flow rates entering into the node and leaving from it, while $\sum_U q_U$ is the sum of the mass flow rates required from the utility.

From the energy balances (see Eq. 1) a number of NP equations is obtained. In matrix form it results:

$$F_P(Q, H) = A_{11} \cdot Q + A_{12} \cdot H = 0 \tag{8}$$

In the same way, from the mass balances (see Eq. 7), NN equations can be written:

$$F_Q(Q, H) = A_{21} \cdot Q - q = 0 \tag{9}$$

It follows a system of $NP+NN$ equations where mass flow rates (Q) and energy contents of the liquid (H) are the unknowns of the problem:

$$\begin{cases} F_P(Q, H) = A_{11} \cdot Q + A_{12} \cdot H = 0 \\ F_Q(Q, H) = A_{21} \cdot Q - q = 0 \end{cases} \tag{10}$$

In Eq. 3, $A_{11}=[NP \times NP]$ is a diagonal matrix in which the non-null terms can be expressed as:

$$A_{11}(j, j) = \frac{\partial F_{Pj}}{\partial Q_j} = \frac{\partial \Delta H_j}{\partial Q_j} \tag{11}$$

In the same Eq. 11, the term $A_{21}=[NN \times NP]$ is the so called topological matrix; the rows of the topological matrix represent the nodes of the network, while the columns are the pipes. It follows, that the generic term $A_{21}(i, j)$ is equal to:

- +1 if the mass flow rate q_j (which flows into pipe j) enters into the node i (it means that the node i is downstream of the pipe j considering the direction of the mass flow rate);
- -1 if the mass flow rate q_j (which flows into pipe j) exits from the node i (it means that the node i is upstream of the pipe j considering the direction of the mass flow rate);
- 0 if there is no connection between the node i and the pipe j .

Finally the term $A_{12}=[NP \times NN]$ is the transpose of A_{21} .

The system can be solved iteratively with Newton-Raphson method generalized in matrix form by Todini-Pilati. At the beginning of the iterative process NP mass flow rates, NN energy contents of the liquid and the direction of the flow for each pipe have to be supposed. With these values, the matrices A_{12} , A_{21} and A_{11} can be written, it follows, for the generic iteration (m):

$$\begin{cases} F_P(Q, H) = A_{11} \cdot Q^{(m)} + A_{12} \cdot H^{(m)} = 0 \\ F_Q(Q, H) = A_{21} \cdot Q^{(m)} - q = 0 \end{cases} \tag{12}$$

By applying the Newton-Raphson method to solve the previous systems, is obtained:

$$\begin{cases} F_P(Q, H) = A_{11} \cdot \Delta Q^{(m)} + A_{12} \cdot \Delta H^{(m)} = -dE \\ F_Q(Q, H) = A_{21} \cdot \Delta Q^{(m)} = -dq \end{cases} \quad (13)$$

where dE and dq are the residuals at the $(m-1)$ iteration; more in details for the generic node i and pipe j , it results:

$$-dq_i = -\left(\sum_{IN} Q_{IN} - \sum_{OUT} Q_{OUT} - \sum_U q_U\right) \quad (14)$$

$$-dE_j = -\left[\Delta H_{pij} - (H_i - H_j)\right] \quad (15)$$

The systems in Eq. 13 needs to be solved in $\Delta H^{(m)}$ and $\Delta Q^{(m)}$.

After each iteration, the values of energy and mass flow rate can be updated as follows:

$$H^{(m)} = H^{(m-1)} + \Delta H^{(m)} \quad (16)$$

$$Q^{(m)} = Q^{(m-1)} + \Delta Q^{(m)} \quad (17)$$

In the developed calculation code, the iterative procedure goes on until the module of each of the terms dq_i and dE_j is greater than 10^{-9} .

3. Ca.R.Di.F. Software

The developed software, called Ca.R.Di.F., can simulate the behavior of a District Heating Network working under given conditions. This software, written in VBA language, can be used for the analysis of a DHN by simulating its behavior or for the design by defining a DHN and starting a trial and error procedure. The working of this software can be represented with the flow chart reported in Figure 4.

It can be observed that the flow chart in Figure 4 strictly follows the mathematical model presented from Eq. 1 to Eq. 17 of the previous paragraph.

More in details, in order to define the matrices A_{11} , A_{12} and A_{21} the input of the DHN are read from the software; the main input are listed below:

- Geometrical input (Cartesian coordinates (x, y, z) for each node, inside and external diameter of each pipe including the insulating material, length of the pipes, pumps position and operational characteristics etc.; in this section also the nodes typology can be defined);
- Utilities input (thermal power required by each of the defined utilities and/or the required mass flow rate, temperature difference between the inlet and the outlet of the primary utility circuit, etc.);
- Sources input (number and position of sources, supply pressure, supply temperature, pressure of the expansion vessel, pump system operational characteristics and performance, etc.);
- Pipe parameters (conduction coefficient of each pipe, roughness, conduction coefficient of the insulating material, etc.).

Similarly, same inputs have to be defined for the return. In this connection, it is important to point up that the software, once defined a supply layout of the network, considers the same geometry for the return, simply reversing the direction of the flow. Thus, the nodes that for supply are sources for the return are considered as utilities; in the same way, the utilities are considered as sources, while the mixers remain the same. With this approach, the flow chart in Figure 4 can be used for both “supply” and “return” calculation.

The outputs of the software are, for both supply and return of the DHN, among the others:

- inlet and outlet temperature and pressure, mass flow rate, velocity, pressure drop for each pipe;
- total mass flow rate supplied from the sources;
- total electrical power for the pumping stations;
- pressure drops at each of primary circuits of the utilities;

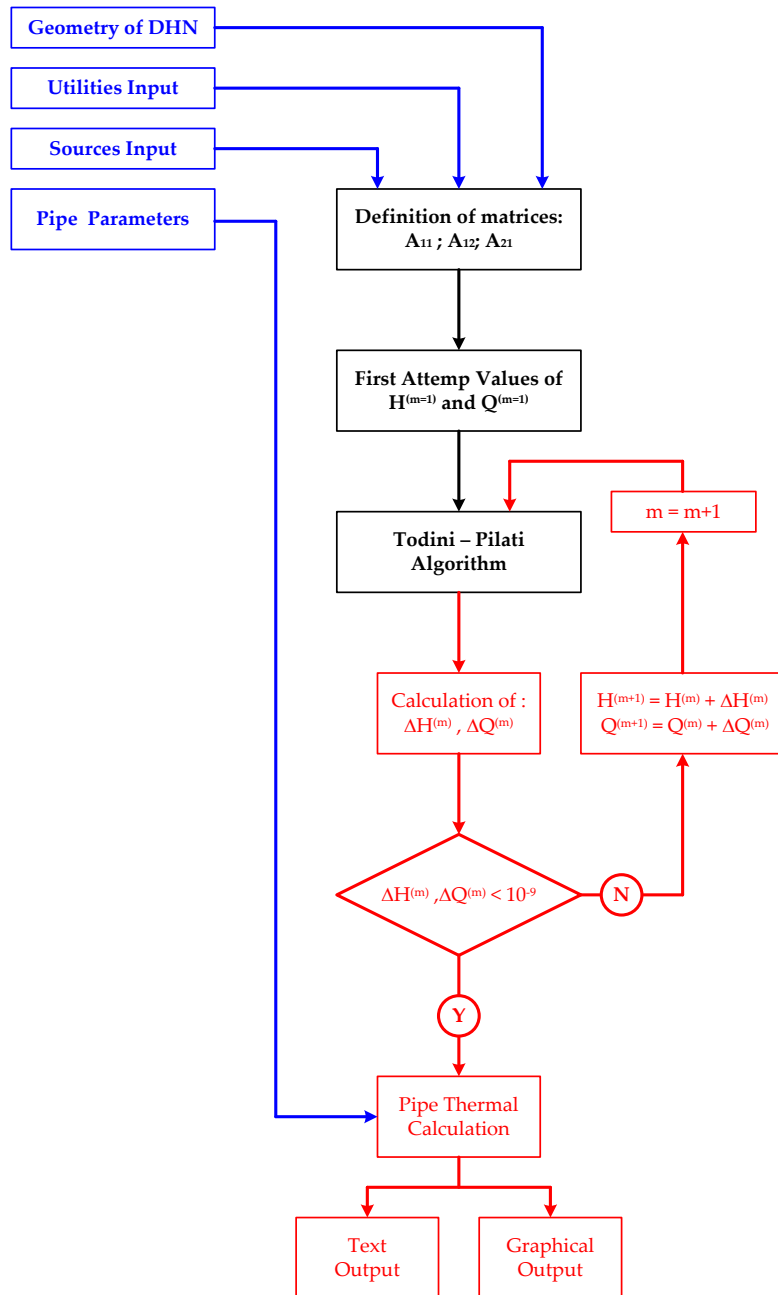


Fig. 4. Main Calculation code flow chart

Moreover, the developed software enables to visualize the network's layout, both for the supply and for the return, with pointers on each pipe to indicate the direction of flow.

With the software Ca.R.Di.F., finally, it is possible to calculate and graph the distributions of velocity, mass flow rates, pressure losses and diameters. The understanding of the representation is immediate, thanks to the use of different colours for the different ranges of the considered quantity.

4. Software validation

With the aim of validating the software previously described, an existing hydraulic network has been considered. This network has been simulated by the Ca.R.Di.F. and the obtained results have been compared with the ones of a commercial software called Termis [10].

The structure of the chosen network, consisting of 95 pipes and 96 nodes (34 utilities, 62 mixers and 1 source), is presented in Figure 5:

The comparison between Ca.R.Di.F and Termis is given in Table 1 where the mean value, the standard deviation and the variance of the comparison between the mass flow rate (Q), pressure and temperature at inlet (P_{in} , T_{in}) and at the outlet (P_{out} , T_{out}), of each pipe calculated by Termis and Ca.R.Di.F. are respectively presented. In the table are considered both the supply and the return of the selected DHN.

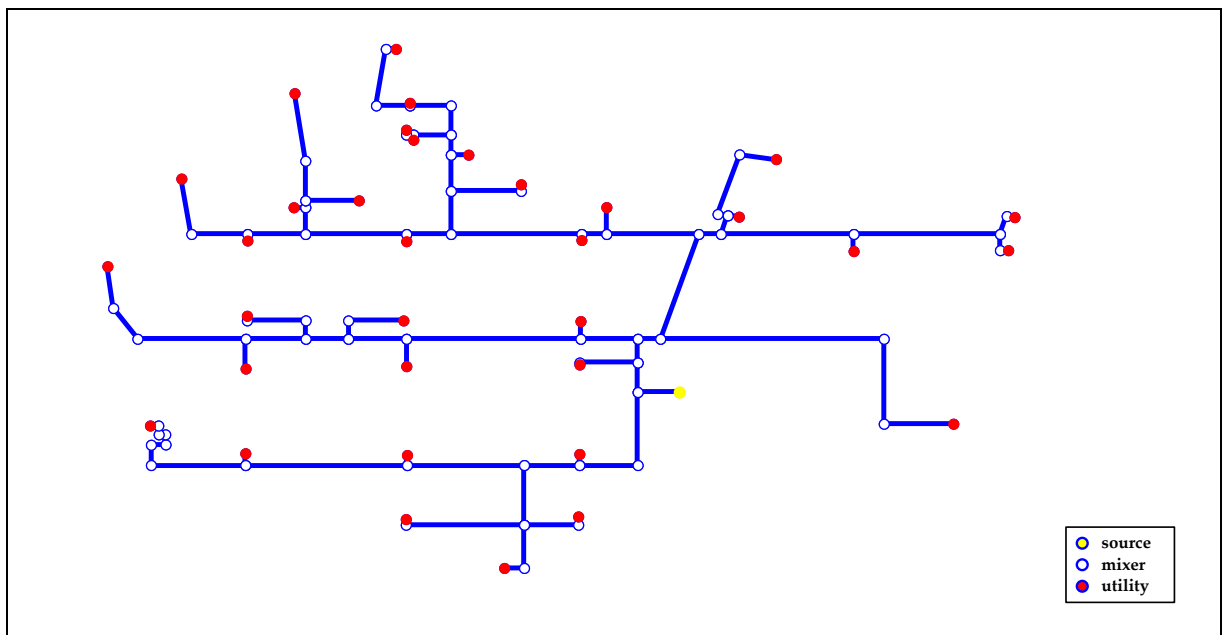


Fig. 5. DHN selected for the validation of the software

From the table it can be observed that there is a strong agreement between the calculation of the two software; it can be seen that the mean value of the ratios between the generic variable calculated by the Ca.R.Di.F. and by the Termis is always greater than 99%; further the maximum values of the standard deviation and variance are respectively equal to about 1.1% and 1.2%.

It follows that the developed comparison validates and confirms the reliability of the developed software. As example, in Figure 6 the pressure profile of the network considering the route from the source to the utility #43 (see Figure 5) is presented as calculated by the two considered software.

Tab. 1. Comparison between Termis and Ca.R.Di.F. calculation

	$\frac{(Q)_{TERMIS}}{(Q)_{CaRDIF}}$	$\frac{(P_{in})_{TERMIS}}{(P_{in})_{CaRDIF}}$	$\frac{(P_{out})_{TERMIS}}{(P_{out})_{CaRDIF}}$	$\frac{(T_{in})_{TERMIS}}{(T_{in})_{CaRDIF}}$	$\frac{(T_{out})_{TERMIS}}{(T_{out})_{CaRDIF}}$
Mean Value [%]	100.00	99.48	99.59	99.96	99.96
Standard Deviation [%]	0.58	1.11	1.09	0.05	0.05
Variance [%]	0.34	1.23	1.19	0.00	0.00

For what regards the stability of the software’s convergence, in Figure 7 the *Mean Total Residual (MTR)* of the chosen DHN is presented. The *Mean Total Residual*, is defined as follows:

$$MTR = \frac{\sum_{i=1}^{NN} |dq_i| + \sum_{j=1}^{NP} |dE_j|}{NN + NP} \tag{18}$$

Also if there is no a physical meaning in the definition of the *MTR* (being defined as the sum of the residuals of the mass flow rates balances and of the energy balances) this value easily represents the fast convergence and the robustness of the calculation method and in particularly of the realized software. From the figure it can be seen that in only four iteration the value of *MTR* becomes equal to less than 10^{-11} ; further, it should be taken into account, as already written, that the iterative procedure continues until each of the residuals is greater than 10^{-9} .

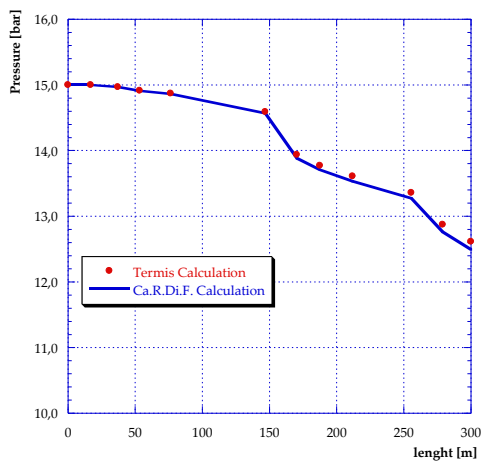


Fig. 6. Comparison between Termis and Ca.R.Di.F. calculation

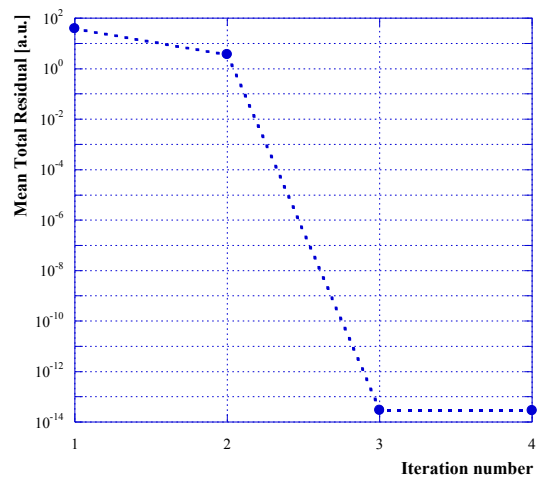


Fig. 7. Mean total residual

Finally, as example of the software’s capabilities already exposed in the previous paragraph, the graphs of the distributions, obtained by the use of the Ca.R.Di.F, of velocity and pressure losses for the analysed network are presented in Figure 8.

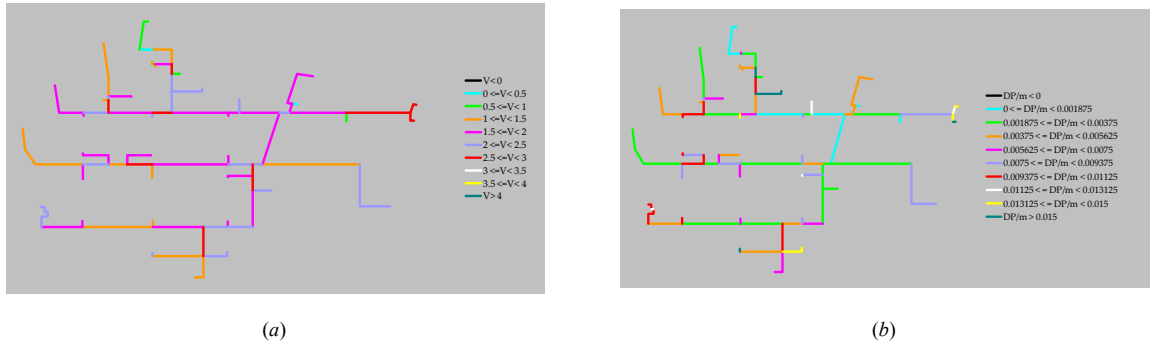


Fig. 8. (a) distributions of velocity [m/s] and (b) pressure losses [bar/m] obtained with the software Ca.R.Di.F.

5. Concluding Remarks

In the last years, the drive for reaching higher conversion efficiencies, has led to an increasing attention on the potential of district heating. In the perspective to a further increase of the diffusion of district heating, the University of Bologna has developed the software Ca.R.Di.F., presented in this study. As widely described in the paper, this software, by the application of the Todini-Pilati algorithm generalized by the Darcy-Weisbach equation, allows the resolution of DHNs and the analysis of the main characteristics of the network by the point of view both numerical and graphic. More in details, Ca.R.Di.F. software, by introducing the DHN geometry is able to estimate the mass flow rates, the pressures and temperatures in each point of the network putting in evidence with a graphical interface the critical routes and/or the pipes characterized by high values of flow velocity or by unacceptable total or specific pressure losses. The software can be used for (i) analyzing and optimizing the existing networks, but also for the (ii) optimal design of new networks or for the (iii) expansion of existing ones.

The validation that has been carried out on the presented network points out, thanks to the comparison with the commercial software called Termis, the validity of the Ca.R.Di.F. (the mean value of the ratios between the generic variable calculated by the Ca.R.Di.F. and by the Termis is about 99.8%).

References

- [1] Annuario Associazione Italiana Riscaldamento Urbano - 2011
- [2] Annuario Associazione Italiana Riscaldamento Urbano - 2012
- [3] Todini, E. (2008) On The Convergence Properties of the Different Pipe Network Algorithms. Water Distribution Systems Analysis Symposium 2006: pp. 1-16. doi: 10.1061/40941(247)75
- [4] Todini, E. (2006). "Towards Realistic Extended Period Simulations (EPS) In Looped Pipe Networks", Proc. 8th Annual Int. Symp. On Water Distribution Systems Analysis, ASCE, Reston, VA.
- [5] Wood D.J. and C. O. A. Charles (1972) "Hydraulic network analysis using linear theory". Journal of the Hydraulics Division, ASCE, Vol. 98, No. HY7
- [6] Epp R. and A. G. Fowler (1970) "Efficient code for steady-state flows in networks". Journal of the Hydraulics Division, ASCE, Vol. 96, No. HY1.
- [7] Kesavan H.K. and M. Chandrashekar (1972) "Graph-theoretic models for pipe network analysis". Journal of the Hydraulics Division, ASCE, Vol. 98.
- [8] Martin D.W. and G. Peters (1963) "The application of Newton's method to network analysis by digital computers" IWES Journal
- [9] Shamir U and C. D. D. Howard (1968) "Water distribution network analysis". Journal of the Hydraulics Division, ASCE, Vol. 94, No. HY1.
- [10] <http://www.schneider-electric.com/products/ww/en/5100-software/5125-information-management/61418-termis-software/>