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A Thermoeconomic Approach for the Analysis of District Heating Systems

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Abstract

District heating is a rational way to use fossil fuels for domestic heating (and cooling) in towns, especially if it is joined with a cogenerative production of electricity. As with every other process it must be economically convenient for its realization, so technical considerations must be integrated into the economic ones. Thermoeconomic theories take into account these two aspects, representing a good tool for an optimized design and correct management (Bejan et al. 1996).

The aim of this paper is to propose the use of thermoeconomic procedures for the analysis of district heating systems, in order to define criteria for the network design. The approach consists of the choice of significant design parameters, which can be varied in order to determine the optimized system.

An application to the Turin district heating system is presented here. The system is composed of a steam power plant and a gas turbine power plant, both cogenerative, and of the pipe network. The effects of the choices in the network project on the working conditions of the system and on the cost of its products are shown. The optimization problem has been solved by evaluating the decision variable under some particular conditions, obtained by solving fluid-dynamic, thermal and thermoeconomic problems for the whole system, corresponding to different values of the supply fluid temperature.

The application of the thermoeconomic theory to the network allows one to determine the effects of the parameters characterizing each user to the cost of the service provided. This information constitutes a tool for making management decisions, like the opportunity and modality for future expansions of the served area.

Key words: district heating, cogenerative systems, thermoeconomic analysis, system management.

1. Introduction

Thermoeconomics is a branch of engineering combining exergy and economic principles (Gaggioli and Wepfer, 1980). The thermoeconomic analysis of an energy system allows one to calculate on a thermodynamic and economic base the cost rate of all the fluxes flowing in, out and through the system, and in particular its products. The cost calculation gives as much information as the representation of the system is detailed. This is more important as the number of products is high, because in those cases the number of components and fluxes, both with physical and productive meaning, is high.

A district heating network is typically a multi-product system, because each heat flow supplied to the final users has characteristics different from the others, in particular different amount and quality. Moreover each user differs from the others for position and time schedule. For those reasons each flux is a different product.

The topological model of such a system is usually made by using the graph theory (Harary, 1996), which is based on the use of two kinds of elements: branches and nodes. Branches represent components that transport a fluid in the space, like pipes, and where the thermodynamic process of fluids takes place. Nodes represent the

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elements where the branches join together (Calì and Borchiellini, 2002).

This representation lends itself to a mathematical expression, made by using a particular matrix, known as incidence matrix (see for example (Chandrashekar and Wong 1982)). The incidence matrix, **A**, is characterized by as many rows as the branches (m) and as many columns as the nodes (n). The general element A_{ij} is equal to 1 or –1, respectively if the branch j is entering or exiting the node i and 0 in the other cases. The use of the incidence matrix allows one to express the balance equation of the flow of the general extensive quantity G_x as:

$$A \cdot G_x + G_{x_d} = 0 \qquad (1)$$

where G_x is the vector containing the values assumed by the quantity G_x in the nodes and G_{xd} is the vector containing the amount destructed in the branches.

This structure can be used for continuity and momentum equations, exergy balance and cost balance (Valero et al. 1986).

2. Thermoeconomic Analysis of a DHN

The case study is constituted of an existing district heating system (DHN), located in the city of Turin (Italy). In this system heat is supplied to the network by a gas turbine (62 MWth) and by a steam power plant (162 MWth), also producing globally 139 MW of electricity (Verda 2001). Additional boilers are used in case of high requests or in case of failures at the main plants. The end users are residential buildings, hospitals and public buildings, up to a total of about $22.5 \cdot 10^6$ m^3. In order to simplify the representation and the analysis of so large a network, the zone of interest has been divided into some areas, each representing a group of buildings. The thermal needs of these buildings are concentrated in a virtual heat exchanger located in the area barycentre. The extension of the main network, represented in *Figure 1*, is about 30 km. In details the schemes of the two power plants and of the network, relative to a group of end users located in the same area, are shown. The analysis has been carried on by using

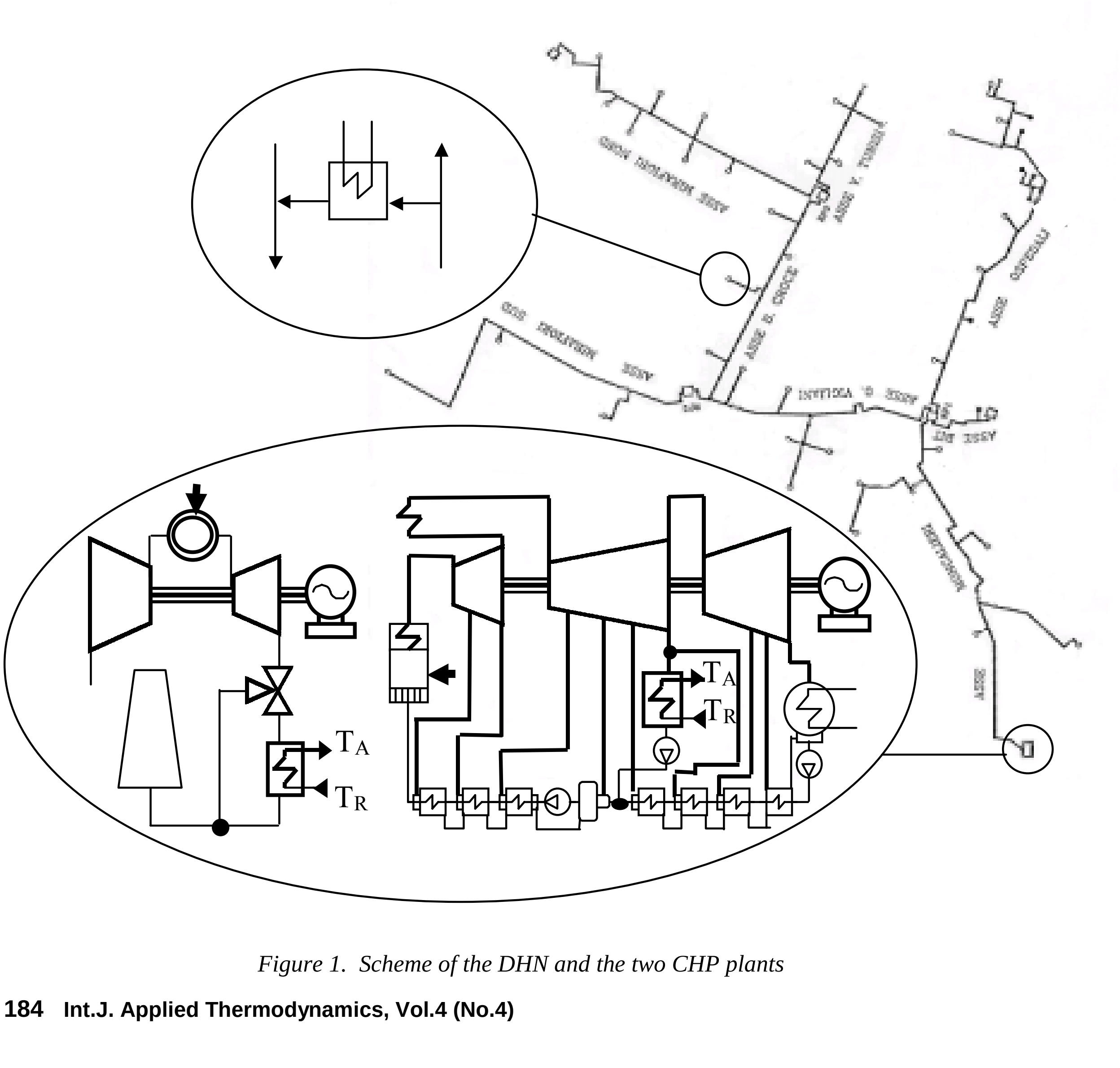

Figure 1. Scheme of the DHN and the two CHP plants

data relative to the conditions in a day of January, which corresponds to a maximum real request, taking into account the non-contemporary maximum request by all the users.

The aim of this study is to point out that a thermoeconomic analysis can make a significant contribution to the optimal design procedure of the whole system. This analysis has been performed by varying the temperature at the exit of the two heat exchangers feeding the network (T_A) and by keeping constant the return temperature (T_R, 60°C), the pinch point temperature difference in the two heat exchangers (respectively 12°C for the steam turbine and 32°C for the gas turbine), the maximum allowed velocity of the water in the pipes (2.3 m/s), the thermal request of each user, the maximum steam mass flow extracted in the steam turbine for cogeneration and the temperature of the flue gas (T>400 K).

The approach to the thermoeconomic problem requires first of all the definition of a productive structure. The physical structure, where each component is characterized by entering and exiting mass and energy flows, is substituted by a different structure, where every component is represented in terms of *fuels* and *products* (Tsatsaronis and Winhold 1985). Fuel is a flow expressing the amount of resources needed by the component to carry out its function, product is a flow expressing the function itself. The products of each component are fuels of other components or overall plant products. In modern thermoeconomics both fuels and products are exergy flows, eventually separated into mechanical, thermal and chemical components (Frangopoulos 1983).

Thermoeconomic theories allow the determination of the costs of the productive flows (fuels and products of all the components), which can be expressed in thermodynamic and monetary units. The solution of the thermoeconomic problem requires writing two groups of equations:

1) the monetary cost balance of every component:

$$\sum_j \Pi_{ji} + \dot{Z}_i = 0 \quad i = 1,2,...,m \qquad (2)$$

where Π_{ji} is the cost rate of the j^{th} flow entering (+) or exiting (-) the i^{th} component and $\dot{Z}_i$ the cost rate of the i^{th} component. If the exergoeconomic unit cost c_{ji} is introduced, defined as the ratio between the cost rate of a flow and its exergy flow rate Ψ_{ji}: Using

$$c_{ji} = \frac{\Pi_{ji}}{\Psi_{ji}} \qquad (3)$$

Eq. 2 becomes:

$$\sum_j \Psi_{ji} \cdot c_{ji} + \dot{Z}_i = 0 \qquad i = 1,2,...,m \qquad (4)$$

2) auxiliary equations, obtained by evaluating the cost of some flows, in particular:
- the unit cost of the overall plant resources, equal to 1 if the exergetic costs are required or equal to the prices of exergy if the exergoeconomic costs are required;
- the unit cost of the product of components characterized by different products; often this cost is assumed the same for all the products.

The whole equation system can be written in a matrix formulation (Lozano and Valero 1993):

$$\begin{bmatrix} A \\ \alpha \end{bmatrix} \cdot \Pi + \begin{Bmatrix} \dot{Z} \\ -\omega \cdot c_\omega \end{Bmatrix} = \begin{Bmatrix} 0 \\ 0 \end{Bmatrix} \qquad (5)$$

where:

α is the matrix containing the coefficients of the auxiliary equations;

ω is the vector containing the evaluation of the exergetic costs, i.e. amount of fuel exergy consumed per exergy of that stream;

Π is the vector of the exergoeconomic cost rates;

$\dot{Z}$ is the vector containing the cost rate of the components;

c_ω is the vector containing the evaluation of the unit exergoeconomic costs.

The application of such an analysis to the two combined heat and power (CHP) plants allows the calculation of the unit costs of electricity (c_w) and thermal flow provided to the DHN (c_T). Those costs depend on the production processes, so they are generally different between them and different for the two plants. Moreover, the thermoeconomic analysis of the DHN allows one to determine the unit cost of the thermal energy flows provided to the end users.

Further calculations have been developed to analyze the influence of the heat exchanger outlet temperature (T_A) on the whole system design, in particular on the cost of its products. This is perhaps the most significant free design variable; the other main system parameters are generally fixed: thermal request, network length (topology), insulation thickness of pipes (for a chosen diameter), and the location of the plants. The enthalpy flow through a pipe cross section can be written as:

$$G_{h_i} = \pi \cdot \frac{D^2}{4} \cdot v \cdot \rho \cdot c_p \cdot (T_i - T_0) \quad (6)$$

A larger pipe diameter is required to keep the water velocity under the upper limit if the temperature of the water feeding the network decreases. If continuous decreasing of the diameter values is considered, the global thermal losses in the network decrease, so the thermal energy flow requested by the network decreases too; the trend presents a decrease in the thermal losses also if only commercial diameters of pipes are considered. *Figure 2* shows the thermal energy flow requested by the network in the two cases of commercial diameters (solid curves) and ideal diameters (dashed curves). The graph also shows the exergy flow requested by the network (bold curves): this quantity decreases in spite of the augmented mass flow, because the average specific exergy of the flow decreases.

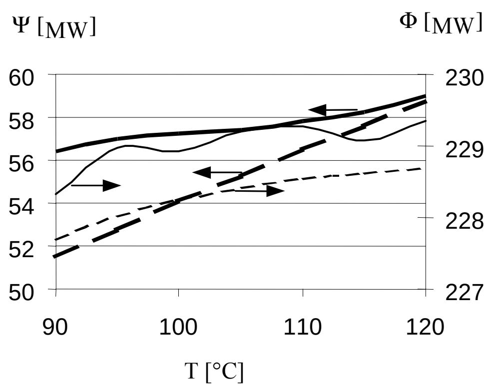

Figure 2. Thermal request of the network.

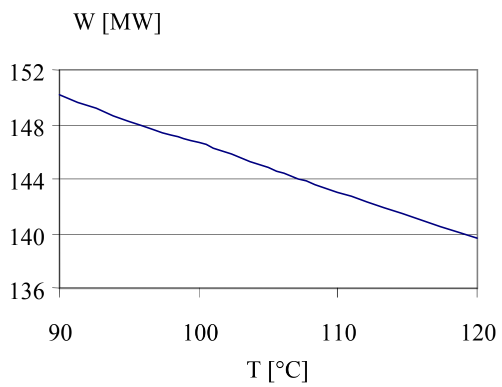

Figure 3. Electric power produced by the system

A second consequence of the lower temperature of the water is the chance of a larger heat exchange in the gas turbine recuperator, as the difference in the pinch point temperature is assumed constant. In this way the steam turbine has to supply a thermal energy flow to the network lower than in design conditions, so the amount of electric power produced by the system can become greater. *Figure 3* shows the possible electricity production of the system as the temperature of the water varies.

On the other hand, the higher the mass flow in the pipes is, the higher the diameters are and so their costs; the power required for pumping increases, too (Calì and Verda 1999). The two terms composing the piping cost, the cost of the pipes (dashed curve) and the cost of the pumping (dashed dotted curve), are represented in *Figure 4*.

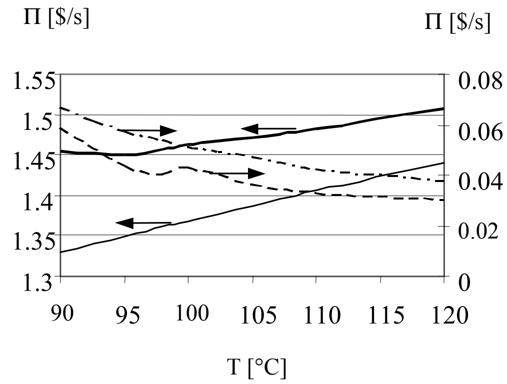

Figure 4. Cost rate of the thermal energy flow

Thermoeconomics applied to the system allows one to calculate the total cost rate of the thermal flow supplied to the network, which is reported in *Figure 4* (thin solid curve). This cost, which is the result of the contribution of the steam power plant and of the gas turbine plant, linearly decreases as the temperature of the water decreases. In both plants the thermal exergy flow provided to the network decreases, as is shown in *Figure 5* (dashed curve refers to the gas turbine and solid curve refers to the steam power plant), but the trend of the unit costs is different.

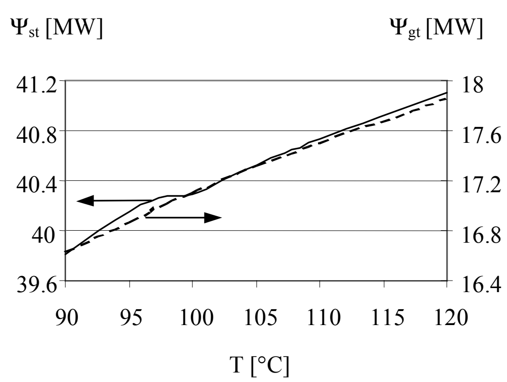

Figure 5. Thermal energy flow provided by the plants

This is due to the different effect of the thermal request and the productive structure on plant behavior (see *Figure 6*). The influence of the production of thermal exergy on the costs can be examined in a simple way considering the two plants as black boxes and applying the cost balance equation to these systems, keeping constant the fuel and varying the thermal request.

$$c_F \cdot \Psi_F + \dot{Z} = c_W \cdot W + c_T \cdot \Psi_T \qquad (7)$$

The average value of the exergoeconomic unit cost of the products is:

$$c = \frac{c_F \cdot \Psi_F + \dot{Z}}{W + \Psi_T} \qquad (8)$$

For the gas turbine (dotted line) it is possible to assume the electric power produced independent of the thermal one, so Eq. 8 prompts an increasing average cost as the thermal exergy decreases, i.e. as the temperature of the water decreases. For the steam power plant (solid line) a lower water temperature causes a lower steam flow extracted for feeding the heat exchanger; this mass flow carries its expansion on in the low-pressure turbine so the amount of electricity produced increases. Both exergy flows written at the right hand side of the Eq. 7 vary, but with a different sign; however the total product of the power plant, measured in terms of exergy flow, increases, as can be understood by looking at *Figures 3* and *5* and considering the electric power provided by the gas turbine plant a constant. The average cost of the unit exergy product becomes lower.

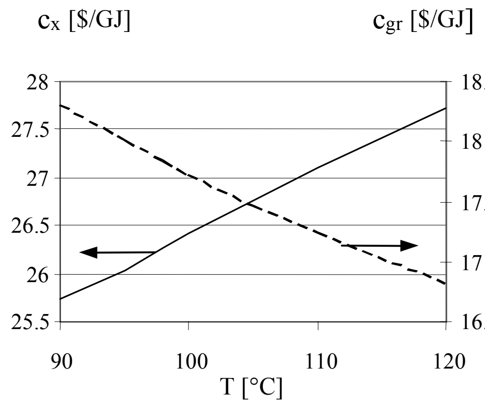

Figure 6. Unit cost of the thermal exergy provided by the plants

Figure 4 also reports the cost rate of the thermal exergy flow supplied by the network (bold curve).

3. Results

The average cost of the two products is shown in *Figure 7* as the temperature of the outgoing water varies. Exergy is assumed as a measure of the product, but usually thermal flows are measured and sold making reference to an energy scale, so it can be useful to transform exergy quantities in the correspondent energy ones. Moreover if the average temperature in every single local network (the network in every building) does not depend on the design temperature in the district heating network, the cost of the exergy flow transferred to the local network has the same trend as the cost measured in energy scale. Therefore if the cost of the service provided is searched, it is most correct to talk about quantities measured in energy scale, otherwise if the cost of the exergy flows leaving the network is searched, it is more correct to use cost referred to the exergy scale. The results are shown in *Figure 8*. The cost curve presents a minimum in correspondence of an outgoing temperature of about 95°C.

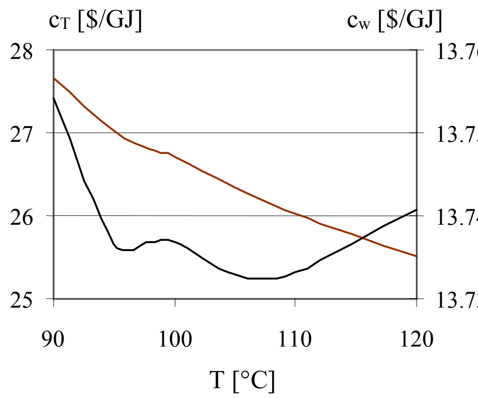

Figure 7. Unit cost of the products

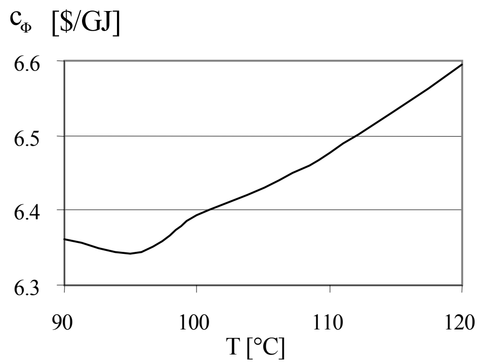

Figure 8. Energy unit cost of the heat supplied

The choice of the working conditions depends on the energy policy; a different solution can be obtained according to the price of electricity and heat. If the minimum of the unit cost of the heat is the objective function, the best temperature will be 95°C, otherwise if the minimum of the unit cost of the electric power is the goal, the best temperature is about 107°C.

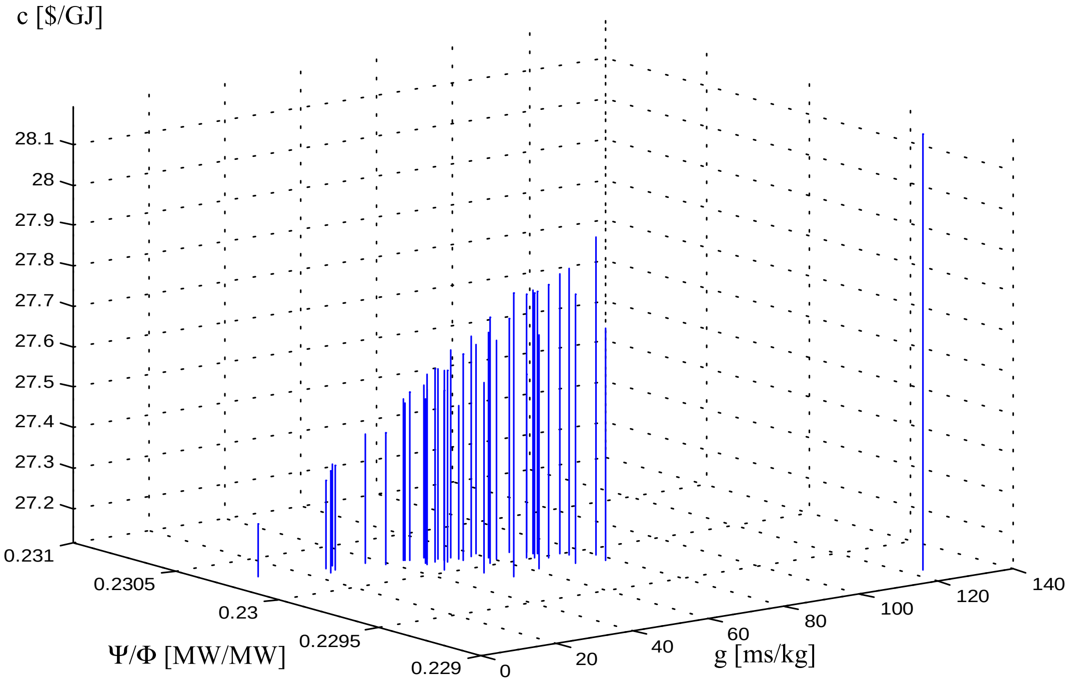

Figure 9. Unit cost of the exergy flow required by the users

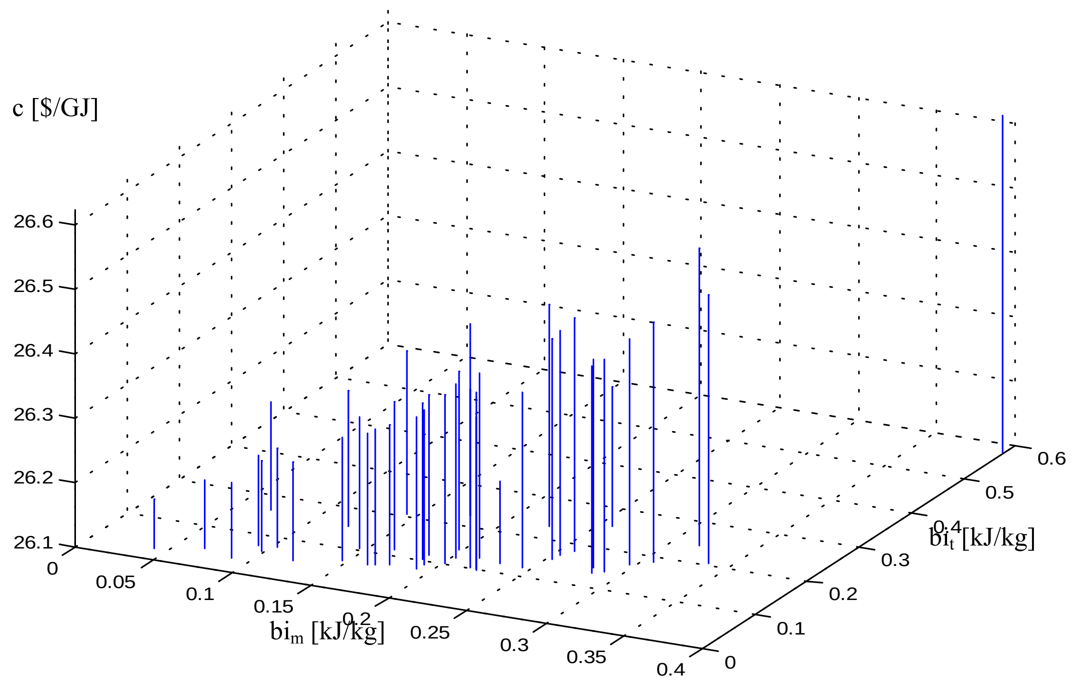

Figure 10. Influence of thermal and mechanical irreversibilities on the cost

A second result shown here is the cost of the heat supplied to every user of the system, in order to determine which parameters most influence it. This thermoeconomic cost is composed of three parts: the cost of the heat supplied by the power plants to the district heating network, the cost of the piping system and the cost associated to the mechanical and thermal irreversibilities. The last two terms are different for every user because they depend on the different paths covered by the water from the central heat exchangers to the user.

In the graph reported in *Figure 9* it is shown that the unit thermoeconomic cost for all the users as a function of two quantities: the ratio between exergy and energy flows of the heat supplied to every user, which takes into account thermal and mechanical losses in the path, and a geometric quantity closely related to the piping cost attributed to the user[1]. This parameter, derived from expressions of the piping cost available in literature (Cammarata et al. 1998), is defined as:

$$g = \sum_{i=1}^{n} k_i \cdot \frac{L_i \cdot e^{a \cdot D_i}}{G_i} \tag{9}$$

where n is the number of pipes in the network, k_i is a parameter, equals to 1 if the i^{th} pipe belongs to the examined path and a is a constant. The analysis of the graph allows to point out that piping constitutes the main parameter influencing the cost of the heat flow supplied to each user.

The dependence of the cost on the mechanical and thermal irreversibilities is shown in *Figure 10*, where the cost of the heat flows does not include the cost of pipes. Mechanical and thermal losses are represented for a temperature of 90°C, using the parameters:

$$b_{i\,m} = \sum k_i \cdot \frac{\Psi_{irr\,m_i}}{G_i} \tag{10}$$

$$b_{i\,t} = \sum k_i \cdot \frac{\Psi_{irr\,t_i}}{G_i} \tag{11}$$

Figure 9 shows that the average exergoeconomic cost of heat supplied depends on the geometric characteristics of the network and on the mass flows, i.e. depends on the geometric parameter g. *Figure 10* shows its dependence on specific irreversibilities. Parameter g could then be a criterion to allocate the piping cost to the users or to predict the cost of a new user. The error on the unit cost of this approximation is less than 0.5%, while the incidence of the piping cost on the total unit cost is an average of 10%.

4. Conclusions

The use of thermoeconomics for the analysis of district heating systems allows one to obtain some useful information for the plant design and management. In this paper both those aspects have been examined.

The temperature of the water flow feeding the network (T_A) has been assumed here as a design parameter. It has been shown how this parameter influences the whole system operation conditions, as the products, electricity and heat supplied to the users depend on it. In this case the optimization problem requires the solution of fluid-dynamic, thermal and thermoeconomic problems, so a general approach for those problems is particularly useful.

Moreover the thermoeconomic analysis of the network allows one to characterize the cost of the service provided to every user, depending on their thermal request and on the geometric characteristic of the paths. The incidence of the piping cost has been shown to be not negligible. The knowledge of this relation allows one to determine, for example, the economic cost of the heat supplied to new users, which constitutes a rational criterion for planning future enlargement of the served area.

Nomenclature

b_i	Sum of specific irreversibilities in paths
c	Exergoeconomic unit cost
c_p	Specific heat coefficient
D	Diameter
g	Geometrical parameter of pipes
G	Mass flow
G_x	Flow of a general extensive variable
h	Enthalpy
L	Pipe length
m	Number of components
n	Number of flows
T	Temperature
v	Velocity
W	Mechanical power
$\dot{Z}$	Cost rate of a system

Greek letters

ρ	density
Φ	Heat rate
Ψ	Exergy flow
Ψ_{irr}	Destroyed exergy rate

Matrices and vectors

A	Incidence matrix

[1] The path joining the plant to the users is easily determined only in case of tree networks, like the one analysed here, where no internal loops occur

c_w Vector of the evaluation of the unit exergoeconomic costs

$\dot{Z}$ Vector of component cost rate

α Coefficient matrix of the auxiliary equations

Π Exergoeconomic cost vector

ω Vector of evaluation of exergy costs

Subscripts

d Destroyed quantity

F Fuel

gt Gas turbine plant

M Mechanical component of exergy

st Steam turbine plant

T Thermal component of exergy

W Mechanical (electric) power

0 Environment condition

Φ Per unit heat

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