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Automatic fouling detection in district heating substations: Methodology and tests

Elisa Guelpa*, Vittorio Verda

Energy Department, Politecnico di Torino, Corso Duca degli Abruzzi 24, 10129 Torino, Italy

HIGHLIGHTS

- The effects of fouling in district heating substations are analyzed.
- A methodology for the fouling detection in large networks is proposed.
- Data gathered by smart meters installed in the system substations are used.
- The potential of the methodology is proved by experimental tests.
- The methodology is implemented in a tool for maintenance activity support.

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Heat exchanger
Malfunction detection
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ABSTRACT

Diagnosis of anomalies in heat exchangers of district heating substations is an essential point to assure high comfort level in buildings, as well as to exploit energy sources efficiently. The aim of this paper is to propose a methodology for automatically detecting fouling in the heat exchangers located in the substations of a district heating system. The methodology is tailored for large district heating networks, where a large number of buildings should be examined with reasonable availability of data. Fouling is analysed using only the data collected by the meters installed in the substations: the mass flow rate on the primary side and the temperatures on both sides of the heat exchanger. Evaluation is difficult due to the rawness of the data gathered and the variable operating conditions, which are adjusted on the basis of the external temperatures and set-points. The software created to implement the proposed methodology receives rough data as the input and it is able to manage data gap and lack of data. Furthermore, it provides a graphical output, which can be used for assisting the operators who manage the network and plan the cleaning schedules. The software has been tested considering space heating substations in six distribution networks of the Turin district heating system, for a total amount of 325 heat exchangers. A regular application of the approach and the cleaning of the heat exchangers presenting fouling is expected to lead to an average annual decrease of about 1.6% of the primary energy consumption in the entire network.

1. Introduction

District heating (DH) allows the exploitation of different energy sources and technologies for house heating in highly populated areas [1]. The core is an insulated pipeline connecting the heat production and storage plants to the consumers [2]. The heat transfer fluid used in more recent networks is pressurized water, which presents smaller heat losses and technical issues than steam [3]. The option of feeding DH with different types of large plants located in a limited number of sites is one of its main strengths, which increases the DH systems diffusion worldwide. This possibility becomes even more interesting when approaching 4th Generation District Heating (4 GDH) concept. In fact, the use of low temperature water also enables the potential of better exploiting renewable energy sources (RES), such as biomass [4], solar [5] and geothermal [6] sources, waste heat from industrial plants [7,8], and cogeneration plants. Another option stand in the use of heat pumps that exploit the DH return water [9]; this enable the possibility of using high performances heat pumps, not only in less dense populated areas [10,11]. All these advantages lead to a reduction of CO_2 emissions, while increasing the fraction of buildings served by DH systems [12].

As a result, primary energy use will decrease while new technology becomes more common [13]. Furthermore, DH fed by combined heat

* Corresponding author.
E-mail addresses: elisa.guelpa@polito.it (E. Guelpa), vittorio.verda@polito.it (V. Verda).

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Nomenclature

A	exchange area, m2
b	specific exergy (J/kg)
c	specific heat, J/(kg K)
F	factor for non countercurrent heat exchangers
G	mass flow rate, kg/s
h	convective heat transfer coefficient, W/(m2 K)
k	conductive heat transfer coefficient, W/(m K)
LMTD	logarithmic mean temperature difference, °C
m	mass kg
NTU	number of transfer units, -–
R_f	fouling factor m2 K/W
T	temperature, °C
t	time, s
U	global heat transfer coefficient W/(m2 K)

Greek symbols

Φ	thermal power
η	efficiency
φ	maintenance factor

Subscripts and superscripts

f	fouling
in	inlet
out	outlet
m_	log mean logarithmic

and power production, RES, energy storage and industrial plants is a promising and realistic option to get close to a 100% renewable society. This is also highlighted by the results obtained in [14], which shows that future estimated capital costs for district heat distribution are rather low, since cities are very dense and the most favourable conditions appear in large cities and in inner city areas.

About two thirds of current exergy content is lost in the heat distribution chain [13]. It is reasonable to assume that in the future a much lower fraction will be lost thanks to (i) a reduction of the difference between average network temperatures and the ambient temperature (ii) tools for optimizing the network management. In this framework, various works are proposed in the literature with the aim of reducing pumping costs [15,16], minimizing thermal peaks [17,18] improving substation regulation strategy, optimizing operations for minimizing overall costs [19]. In particular, the control system installed in each substation [20,21], typical for 4GDH, are starting to enhance potential for an optimized management of the various heat sources [22]. New generation networks take advantage of opportunities offered by control systems for avoiding pointless energy losses. This issue becomes crucial when DH systems grow in size so a proper control strategy has to be used for a smart use of primary energy, in both normal operating conditions [23] and during unexpected events, such as malfunctions and failure [24].

In this framework, one of the main issues for the energy companies which manage DH systems regards the effectiveness of the heat exchangers installed in the thermal substations. High performance substations represent a crucial aspect for efficient 4GDH [25]. An important issue is the presence of fouling, i.e. the deposition of undesired particles on the heat transfer surface, which creates an additional layer of material reducing the heat-transfer coefficient. This problem is very relevant, as discussed in [26] where the worldwide costs for fouling of heat exchangers, in crude oil distillation, is estimated to be of the order of $4.5 billion/year.

Once the presence of fouling becomes significant, a maintenance intervention should be planned for re-establish the thermal performances of the heat exchanger. In the case of braze welded heat exchanges, the device must be replaced while other types of heat exchangers can be cleaned. In [27] a discussion on mitigation strategies and cleaning techniques is reported. The problem of fouling exists in all DH networks but it is more difficult to manage in large networks, where the number of connected buildings is often above several thousands. In these cases, it is not possible to plan in situ inspections by the technicians. Indeed only in small networks, it is possible planning periodical control directly in the substation location in order to detect possible fouling deposition.

In the literature, various papers deal with fouling detection in heat exchangers. As regards the analysis in situ, in [28], a probe is proposed to evaluate the convective heat transfer coefficient and the thickness of the fouling layer. The approach is based on the comparison of the global response time of the system in state of fouling and cleanliness. This is suitable for very small networks with a limited number of heat exchangers where it is possible to monitor the various components periodically, when there are clues that some components are not working properly. An accurate shell-side heat transfer coefficient and fouling factor estimation has been provided in [29]. The analysis is performed using an experimental approach and it is applied to heat exchangers with parallel helical tube coils. This can be used for further design of heat exchangers in district heating systems.

Concerning DH applications, an experimental analysis on plate heat exchangers in the Belgrade DH is presented in [30]. It reveals that, for radiator water heaters, the fouling factor changes in narrow range, while the fouling factor of domestic hot water heaters strongly depends on the water velocity.

As regards on-line detection, various methods are proposed when pressures, temperatures, mass flow rates and thermo-physical properties of both heat-exchanging media are known [31] or, temperatures, mass flow rates and geometry of the heat exchangers [32]. In [31], measured data are used for on-line evaluation of the thermal resistance of fouling in shell and tube heat exchangers, while in [32] an approach for quantify the influence of fouling on the heat recovery in industrial HENs is proposed. Both approaches use data acquired during periods of normal plant operation.

In [33], the C-factor, calculated as the ratio of the overall heat transfer coefficient in fouled and in clean conditions, is used to evaluate the extent of fouling and the performance of a heat exchanger. The fouling parameters are evaluated though measurements of flow rate and pressure drop in transient state. In particular, the C-factor is compared with its value in clean conditions. The fouling parameters are predicted by measurements of flow rate and pressure drop. This represents an interesting approach when the measurements of the pressure drops are available.

This paper aims at proposing a methodology for the automatic detection of fouling in DH systems. The main strengths of the tool presented here, which also represent the main novelties of this paper with respect to the approaches available in the literature (see Section 3), are:

(1) No specific modelling of the heat exchangers, taking into account its true configuration, is necessary. This piece of information is typical difficult to consider. This is even more complex in the case of old networks where many heat exchangers are installed along the years and no proper description of the units is available. This problem is typical of large DH networks, with many buildings connected. The proposed approach utilizes data recorded by classical metering equipment, which are often installed in the substations for control and/or billing purposes. These devices record temperatures and mass flow rates, together with the various settings, alarms, etc.

(2) A second advantage of the present methodology is that it does not require measurements of pressure drops at substations, which are usually expensive and not always included in the classical instrumentation. In DH system substations, flow meters and temperature meters are generally installed for billing purposes. In contrast pressure meters are generally not installed in substations but in strategic points of the network, such as pumping stations and valve rooms [34–36]. This is mainly due to the purchase and installation costs and because these sensors are not mandatory equipment [37].
(3) Moreover, in contrast with various approaches available in literature, performances are evaluated by using data recorded also during transient operation. The model automatically evaluates a proper time-frame, when the system works in quasi-steady state conditions and utilizes the corresponding data in order to perform the analysis.

For all these reasons, the approach upon the proposed tool is based can be considered as a new and general methodology for the evaluation of the fouling in DH networks. The generality is mainly due to the few data required by the system and independence on the heat exchanger type, dimension and network size and typology. The methodology has been incorporated in a software, which can automatically applied to the analysis of large DH systems. In this work, it has been used to analyse heat exchangers for space heating in six distribution networks of the Turin DH system proving to be a valuable tool for the technicians in charge of the maintenance.

The main research items presented in the paper are:

1. To propose an innovative technique for the automatic detection of fouling in large DH network where no additional information is available except for data recorded by the classical metering equipment (knowledge of heat exchanger geometry is also not required) (Section 3). The methodology is validated using experimental data. Results of the methodology application on an extended DH system are shown (Sections 5.2 and 5.3).
2. To evaluate the effects of detection and cleaning of the heat exchangers fouled, on the primary energy consumption of the DH system (Section 5.4).

2. Methodology

This paper has the aim of proposing a novel approach for the automatic evaluation of fouling that is tailored for large DH networks using the following data:

- mass flow rate on the primary side of the heat exchanger;
- temperature at the inlet and outlet sections of both sides of the heat exchanger.

Information about pressure drops and heat exchanger geometry are not required. This represents an important issue in large DH network,

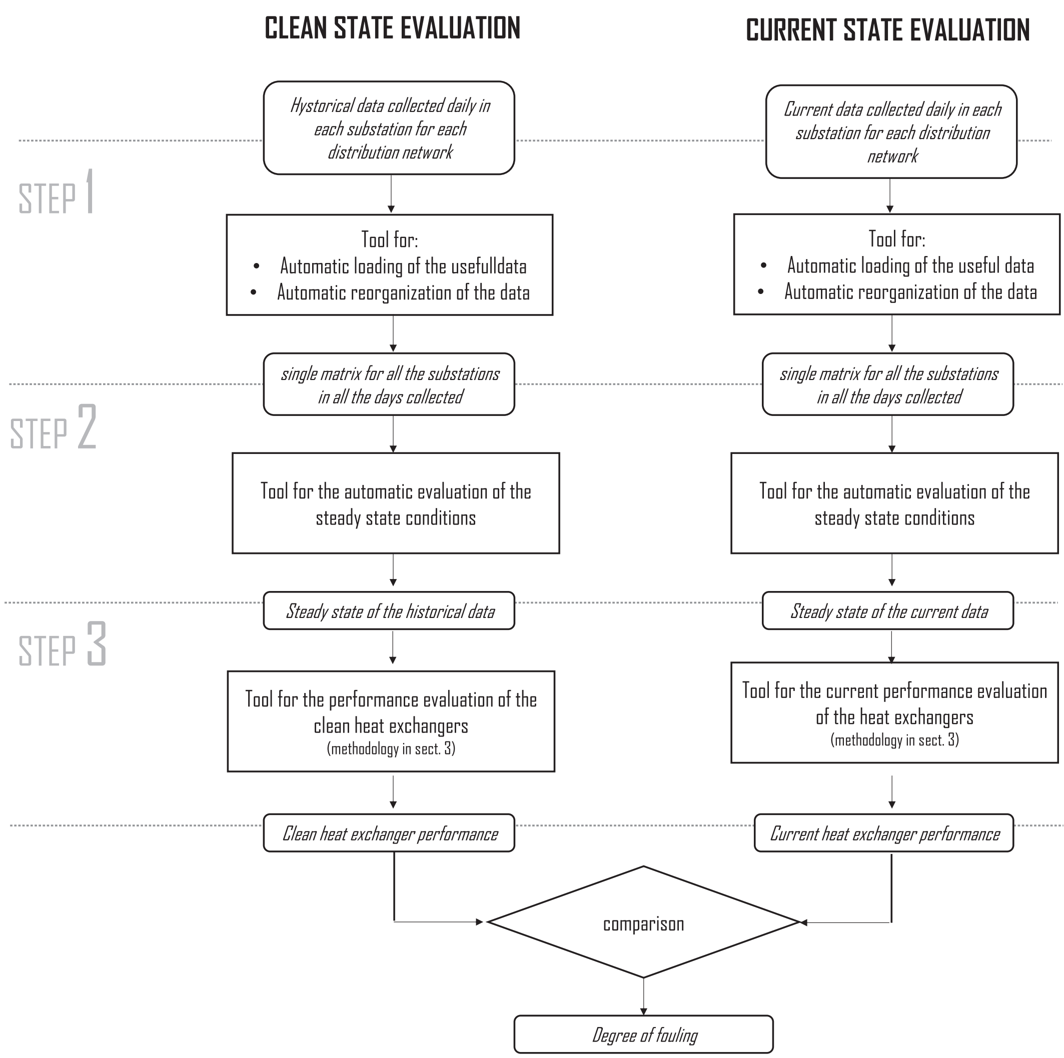

Fig. 1. Steps for the evaluation of the degree of fouling.

because:

metering equipment installed in the DH substation usually do not include pressure meters, which are expensive devices.

large DH networks have usually grown with continuous addition of pipelines and substations; therefore, a complete description of the geometry and typology of the various heat exchanges, installed in different times, might be not available.

A software for its implementation has been created. It receives data directly collected from the metering equipment as the inputs. These are rough data usually referring to transient conditions, and it performs a pre-processing for making them suitable for the analysis. Furthermore, it provides a graphical output that makes even more useful to the DH network operators.

The status of a heat exchanger can be expressed as the product of the heat transfer area *A* times the global heat transfer coefficient *U*:

$$UAF = \frac{\phi}{\Delta T_{mlog}} \tag{1}$$

The factor F takes into account that the heat exchangers are not perfectly operating in counter-flow configuration. This factor is affected by the operating condition of the heat exchanger, therefore it changes with the thermal demand of the substation. The quantity ΔT_{mlog} is the mean logarithmic temperature difference. When fouling occurs, the product UAF varies following the relation indicated in equation (2).

$$UAF = \frac{1}{\frac{1}{A_i h_i} + \frac{Rf_i}{A_i} + \frac{s}{Ak} + \frac{Rf_o}{A_o} + \frac{1}{A_o h_o}}\mathrm{F}$$

The fouling factor Rf is defined as a measure of the thermal resistance due to fouling. Rf is zero in clear heat exchangers and increases during the particle deposition. In particular, according to Kern and Seaton [38] the following expression is valid for heat exchangers:

$$\frac{dm}{dt} = m_i + m_o = (\rho k)_f \frac{dRf}{dt} \tag{3}$$

where m is the fouling mass and the subscript f indicates the fouling properties.

Fouling leads to a reduction of UAF. The analysis of evolution of UAF and the logarithmic mean temperature difference (LMTD) during operation allows to quantify the presence of fouling inside the heat exchanger. An analysis of UAF and LMTD in clean and fouled conditions is provided in Section 5.2, in order to compare the quantities that can be used for fouling detection. The values of UAF increase when the heat flux exchanged increases, mainly because of the presence of the factor F, which tends to 1 when the mass flow rate on the primary side is large. For this reason, fouling analysis is performed considering the time evolution of the curve UAF as the function of the heat flux exchanged. In particular, the slope of the curve is used as the parameter to account for the fouling level. It consists on the average inverse of LMTD. This approach is particularly suitable because it allows evaluating the fouling level only by considering the variation of a single parameter. The main problem while evaluating of UAF is due to the fact that it can be done only when the geometry is perfectly known (Eq. (2)). When the geometry is not known, a suitable approach consists in collecting the data necessary for calculation of ϕ and LMTD from the metering equipment.

3. Tool development

An overview of the automatic tool for the detection of anomalies in DH substations is shown in Fig. 1. The software is based on the main ideas of evaluating the working conditions of the heat exchangers in both clean and fouled conditions using data gathered by the metering equipment installed in the substation. This approach allows one to overcome the issues related with knowledge of heat exchanger geometry and the use of heat exchanger design models. To this end, two series of data must be generated starting from the rough metering equipment data:

- Historical data for the evaluation of the clean conditions, which are used as a basis for the comparison with the current state (Fig. 1 left side). The use of old data lies in the necessity of catching a time when the heat exchanger data was clear. With this aim, the oldest available data after a cleaning maintenance, or a substitution, are used.

Current data for the evaluation of the current heat exchanger state (Fig. 1 right). It is important to consider a sufficiently wide amount of data to be sure that fouling is detected and false alarms are filtered off. Indeed, it is important to select an amount of data sufficiently large to obtain a proper estimation of the curve UAF(Φ). The set of data should cover a wide range of thermal requests. This strongly depends on the climatic conditions. For the Turin climate, a reasonable amount of data is two months, since weather conditions are quite variables and climate is not harsh. In hasher climate where the thermal request significantly varies, a wider range should be considered.

For obtaining both the clean and current heat exchange conditions, various pre-processing stages are included in the software. Indeed, the infrastructure of the platform that is linked to the metering equipment for the data gathering, saves the data of all the substations daily. This is done for all the distribution networks. Data are detected every five minutes in our application. Therefore, considering long periods, such as years, a huge amount of data is stored. The automatic fouling detector consists of the following main steps:

STEP 1: loading the rough data and creation of the matrices, which include only the data useful for the analysis. In fact, once the data have been gathered they have to be reorganized for making them suitable for the fouling factor evaluation. Each file corresponding to the data of a specific day for a specific distribution network is loaded and put together with the data corresponding to the previous days. This allows obtaining a matrix where the number of columns is equal to the number of substations, while the number of rows is equal to the number of time frames considered. Number of columns is in the order of 10^5 each year. A proper kind of data format has to be used for managing large data sets; in this work data have been stored in compressed chunks.

STEP 2: automatic evaluation of a period when the heat flux supplied to the building is about constant (i.e. it is only affected by small oscillations). Evaluation of the performances, for being meaningful, must be performed during steady state conditions. An important step consists in an automatic evaluation of the stationary condition during the day. To this end, two values are previously selected: (i) the allowed tolerance of heat flux oscillation, (ii) the minimum time frame that the steady state conditions must last. Once selected these values, the daily load evolution is scrolled until a time period which satisfies the conditions (i) and (ii) is found. This approach has to be used for each building in all the distribution networks. For this reason, a routine is used in order to scroll all the substations of the various distribution networks for all the considered days. In the result section, the performances of this step are shown.

STEP 3: the evaluation of the heat exchanger performances. The parameters used for fouling detection is the relation between UAF and the heat flux exchanged. To avoid falling into false alarms, several values of UAF(ϕ) are considered. The fitting curve of all the data is used for comparison. The terms UAF and ϕ are related through the logarithmic mean difference. In particular, the relation is linear because the logarithmic mean difference is almost constant during steady state operation. For the aim of this work, a first order interpolation line is considered as the indicator for performance variation. This choice is sustained by an experiment which has been done with one of the heat exchangers connected to the DH network before and after its substitution. The outcomes of the test are reported in the result section.

The results obtained after these steps are compared in order to understand if a reduction in the performances had taken place or not. As data pre-processing is time consuming, it is run only periodically order to refresh the heat exchanger performances in clean conditions.

4. Case study

The proposed tool is applied to the Turin DH, which is the largest in Italy and among the largest networks in Europe. The high number of heat exchangers makes it necessary the use of an automatic device for the detection of anomalies. Heat exchangers in the substations are plate heat exchangers. For the details on the network considered, such as dimension, topology, pumping system and power plants, the reader can refer to [39].

The area that has been selected as the testing case is the area around the technical University. The choice is made because this area can be considered as representative of the Turin DH system. It includes six distribution networks, amounting to 325 buildings. The buildings are quite different in terms of volume, year of construction and energy demand profile [39]. In each building is located a substation where a heat exchanger is installed.

As mentioned before, the data used for the estimation of the heat exchanger fouling factor are gathered through metering equipment installed in the substations. These devices usually measures the mass flow rate on the primary side (DH networks side) and the temperatures of the streams entering and exiting both sides of the heat exchangers. The various quantities measured by the metering equipment are detailed in Table 1.

In Fig. 2 the data collected by 10 metering systems installed in one of the six analysed distribution networks are depicted. The daily evolution of the quantities listed in Table 1 are reported in the figure, in order to provide a global picture of the trends (schedule, working conditions and magnitudes). Buildings are selected as representative of different sizes and settings of the heating systems.

The time evolutions of the mass flow rates (G) and thermal power (ϕ) show the schedule of the heating systems. The schedule is intended as the time when the heating system is switched on and switched off. Most of the systems are switched off during the night and are switched on between 5 a.m. and 6 a.m. Furthermore, mass flow rate and heat request evolutions show the daily number of shutdowns of the system, through the number of times they turn to zero. Some systems are switched on just once a day while others present two or three stops. The presence of various stops leads to the presence of various peaks.

Temperatures at the inlet section of the heat exchangers are around 117–119 °C on the primary side. This is due to the fact that the considered network uses water at 120 °C and the thermal losses along the pipelines make the temperature lower. Temperature in the outlet section of the primary side of the heat exchanger are mainly around 55 °C with variations between 45 °C and 70 °C, depending on: (i) the heat exchanged with the secondary circuit (ii) the mass flow rate (iii) the inlet temperature. As regards the evolutions of temperatures at the secondary side, during the working hours, they range between 40 °C and 70 °C.

5. Results

5.1. Validation of the tool for evaluating steady state conditions

The model automatically evaluates a time-frame when the system works in quasi-steady state conditions. This is done as reported in STEP2. The outcomes of STEP 2 for sixteen representative substations included in the six distribution networks analysed in this work are depicted in Fig. 3. The figure shows the evolution of the thermal demand (plain line) and the value of the thermal power in steady state condition, evaluated by the automatic tool (dashed line). The substations reported in Fig. 3, are randomly selected between those included in the analysis. This is done in order to show the reliability of the tool for the automatic selection of the steady state condition. The figure shows that steady state is captured independently from the amount of thermal request, the number of stops and the shape of the curve representing the daily evolution. The discrepancy between the thermal load values during the quasi steady state (plain line) and the calculated steady state value (dashed curve) is lower than 5%.

5.2. Methodology validation

In Fig. 5, the quantity proposed for fouling detection is compared with alternative quantities in order to show the advantages associated with this choice:

- UAF as a function of ϕ where the angular coefficient represents the ratio 1/LMTD;
- UAF as a function of G, where the angular coefficient is proportional to NTU;
- LMTD as a function of ϕ, where the angular coefficient represents the product UAF
- LMTD as a function of G, where the angular coefficient is proportional to 1/NTU;

Results for two tests have been reported, including data precleaning and post cleaning; these are data of two heat exchangers that have been cleaned during the years 2016–2017. All the quantities allow detecting the presence of fouling, since in fouled condition UAF is expected to be smaller and NTU is expected to be larger than in clean conditions. However, the quantity used for the detection should take into account the variation occurring while increasing the thermal demand at the heat exchanger. Furthermore, the evolution should be converted in a quantity suitable for automatic detections.

Evolutions of UAF(ϕ) and UAF(G) are similar, however in case of UAF(ϕ) the distribution is more linear and this allows relying on the evaluation of the curve slope in order to detect fouling (as can be clearly noticed in TEST 2). As concerns the use of LMTD, this is an interesting option. However, its values slightly varies while thermal demand at the heat exchanger increases. In case of fouled heat exchangers, the evolution is much more evident. This means that the possibility of detecting fouling by using LMTD strongly depends on the heat flux at the heat exchanger. The LMTD is a quantity that in some conditions allows proving that the fouling deposition is significant, but this is not always sufficient. For this reasons, as a primary quantity to detect fouling the slope of the evolution UAF(ϕ) is used.

A series of tests on some heat exchangers has been performed in order to prove the capability of the relation UAF(ϕ) of catching the presence of anomalies. In particular, data of some heat exchangers, of the distribution networks included in the analysis, that have been cleaned during the years 2016–2017, have been considered. The 7

Table 1
Data collected by the metering equipment.

Quantity	Location	Symbol	Unit
thermal power	Exchanged at the substation heat exchanger	ϕ	kW
mass flow rate	At the primary side	G	kg/s
temperature	inlet section of the primary side	T1	°C
Temperature	outlet section of the primary side	T2	°C
Temperature	outlet section of the secondary side	T3	°C
Temperature	inlet section of the secondary side	T4	°C

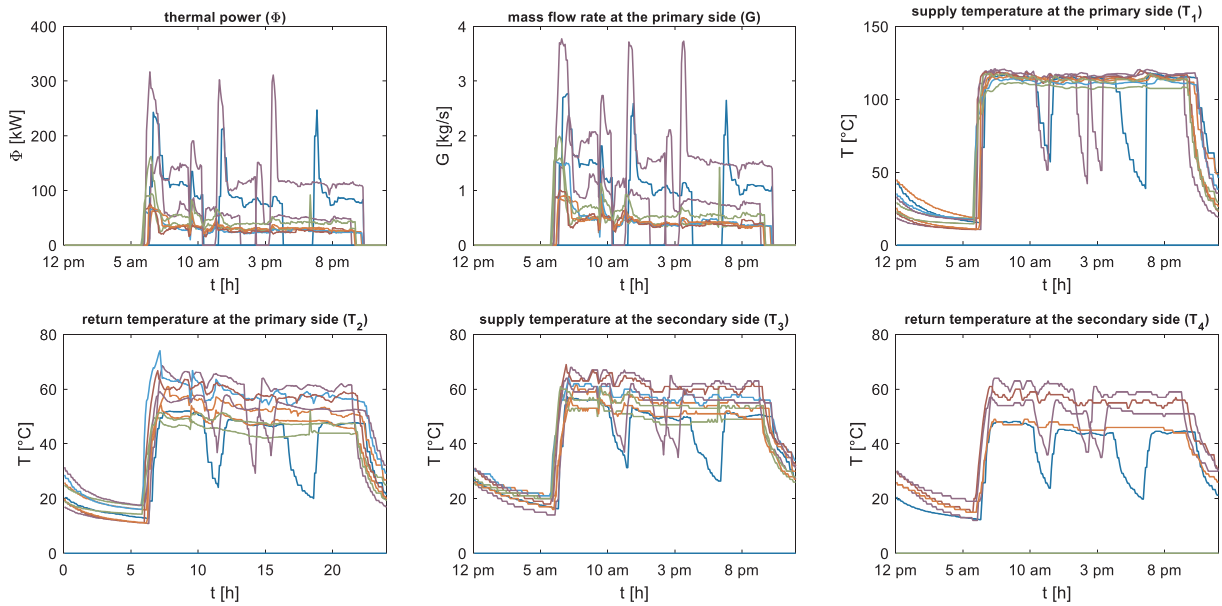

Fig. 2. Daily data gathered in the substations (different colors for the various substation).

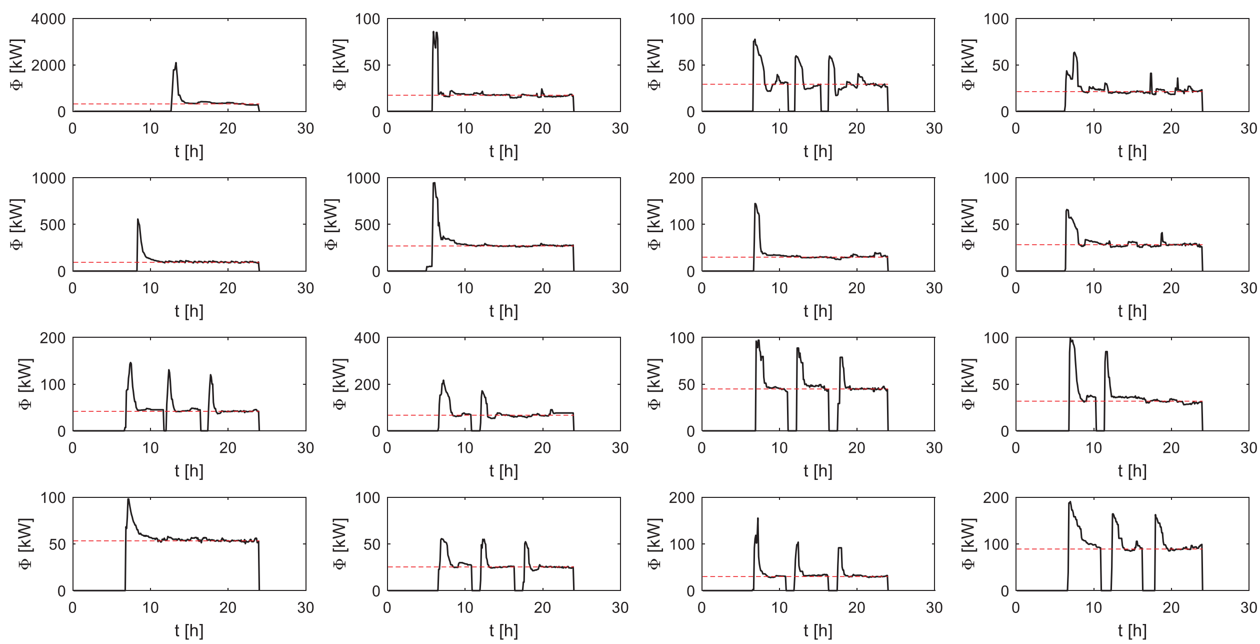

Fig. 3. Results of the automatic evaluation of the steady state condition.

substations used for the analysis satisfy the following requirements: (a) the have been recently cleaned; (b) enough data are available from the metering systems to evaluate the fouling level; (c) the substations are characterized by different values of thermal request. These also include the two tests considered in Fig. 4. Results are reported in Fig. 5. The figure shows a comparison of the relation between UAF and ϕ, in the days before the cleaning (black squares) and the days after the cleaning (red circles). The figure clearly shows that the data of the pre-cleaning period are characterized by a lower ratio UAF with respect to the post-cleaning period. The evolution of the UAF as a function of the heat flux is not perfectly linear in all the considered cases. In cases 6 and 7, a high dispersion is registered. This is due to the fact that data have been registered during variation in fouling deposition. Dispersion is partially due to a high variability in the operating conditions of the substation. However, also in these cases the evaluation of the slope of the linear relation UAF(ϕ) allows to detect the presence of fouling. This outcome suggests that the relation between UAF and ϕ is a useful indicator for the detection of fouling in heat exchangers.

In Fig. 5, the interpolation lines are also reported for both the pre-cleaning and post-cleaning period. Results clearly show that in all the considered cases the slope of the fitting line is lower in case of pre-cleaning conditions. For a clearer interpretations of the results, the values of slope and LMTD before and after cleaning have been reported in Table 2. The slope variation with respect to post-cleaning is always non-negligible and, in some cases, large: between 20% and 60%. This means that in all the cases in which fouling was observed on the heat exchangers, the phenomena could be highlighted by a slope change. The maximum heat flux suggests that the approach used is validated for heat exchangers with different sizes.

The slope in the pre-cleaning conditions strongly depends on various factors:

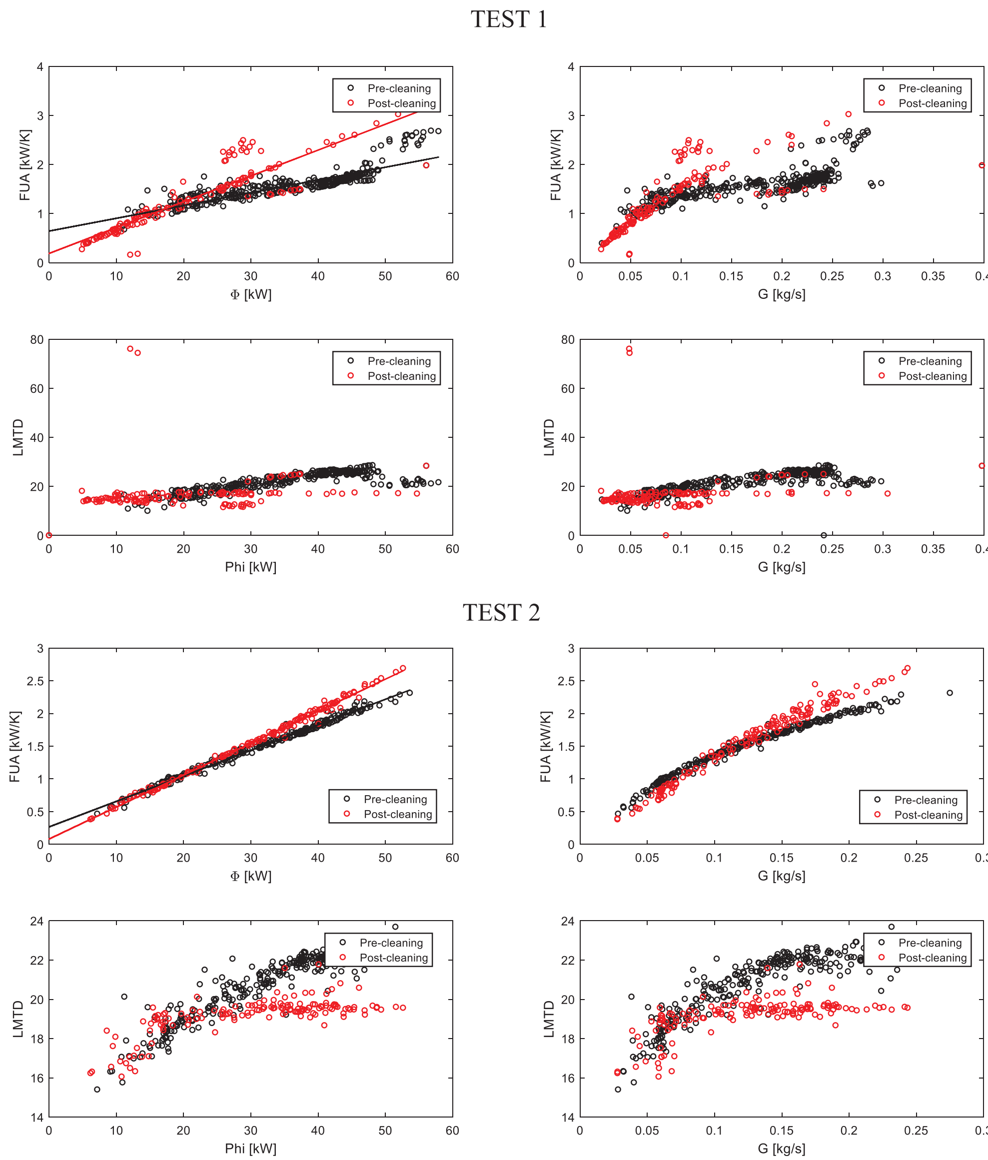

Fig. 4. Comparison between quantities for fouling detection: comparison before and after cleaning.

1. The fouling deposition time; in fact the fouling deposition is not an immediate phenomenon and therefore values progressively deviate from the behaviour of clean heat exchanger.
2. The number of historical days considered in the analysis before the fouling deposition occurs.
3. The time when maintenance was conducted.

The analysis allows identifying some ranges that state when a heat exchanger is fouled or partially fouled. In particular, results shown in Fig. 5 suggest that the following indicators can be used for the relative percentage reduction:

- 0–15% indicates clean conditions;
- 15–25% indicated users partially fouled conditions;
- > 25% indicates the heat exchangers with high fouling.

5.3 Outcome of the field test

The methodology has been used to build a software for the automatic evaluation of fouling in DH networks. As reported in section 4, two series of data must be used for the analysis, i.e. the data for the evaluation of the clean conditions, and the current operating conditions.

As regards the historical data, all data since the last cleaning have been used, except for the ones related to the last month. Regarding the dataset for the evaluation of the current conditions a sufficient number of data are necessary in order to detect fouling and do not fall into false alarms. Data referred to the last month are considered.

Concerning the applicability to networks with different topology, the distance from buildings to plants and the number of connected buildings only affect the inlet temperature to the substations. Nevertheless, as thermal losses are small in percentage during steady state conditions, differences in the operating conditions of the various heat exchangers are small. Fig. 2 shows that all temperatures are around 115 °C. After the evaluation of the fitting line for both clean and current conditions, the values are compared in order to catch possible fouled heat exchangers. The values are reported in Section 5.2. The designed software allows a clear visualization of the condition of all the heat exchanger included in the DH network. In particular, the tool displays the fouling conditions of the heat exchangers in a map, including the location of each substation. In Fig. 6 the outcomes of the software are displayed for the six distribution networks analysed in this work for a total of 325 substations, while Table 3 reports the aggregate numbers for each distribution network. Fig. 6 has a demonstrative aim.

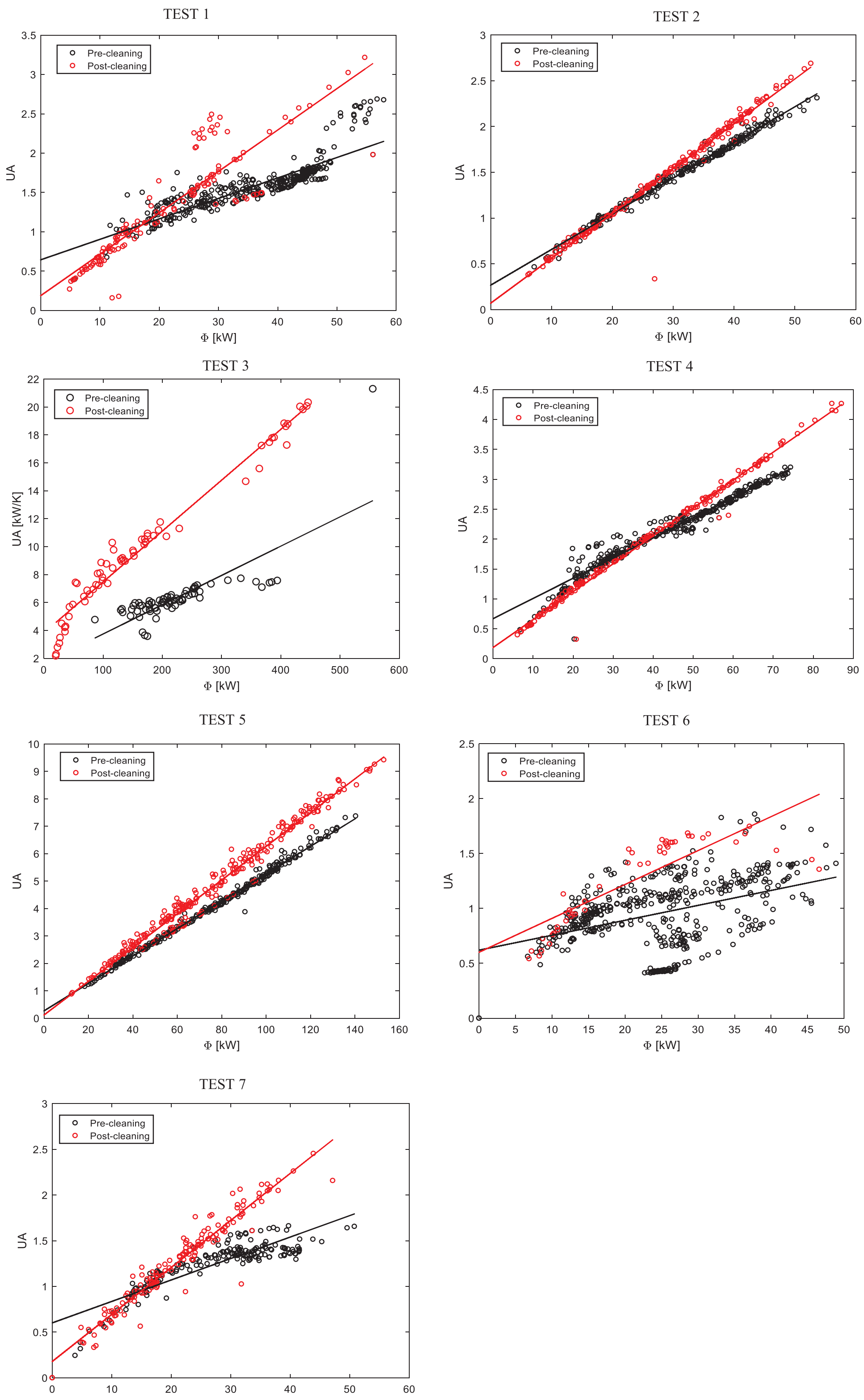

Fig. 5. Validation of the methodology trough experimental data: comparison between pre-cleaning and post-cleaning conditions.

It allows clarifying which are the potential of the tool proposed at large scale (such as for large DH networks). The green points indicate the substations which do not present fouling, while the red circles represents the substation that may be affected by deposition of fouling. These points includes the buildings that are affected by medium or high fouling level and the building that cannot be analysed. For some of the buildings, not enough data are available the day of the analysis (the number of dropouts is 98, i.e. about 30% of the examined substations).

Table 2
Slope reduction of the UAF(Φ) interpolation line due to fouling deposition (experimental analysis).

	Φmax [kW]	Slope in clean conditions [K^{-1}]	Slope variation [%]	LMTD in clean conditions [K]	LMTD fouled conditions [K]
TEST 1	58	0,055	57	18	43
TEST 2	54	0,050	20	20	25
TEST 3	563	0,036	42	28	49
TEST 4	87	0,045	28	22	30
TEST 5	154	0,061	56	16	37
TEST 6	49	0,029	51	34	69
TEST 7	52	0,046	54	22	48

Table 3
Status of the heat exchangers in the examined networks.

	# Substations	# Clean Substations	# Fouled Substations	# Dropouts	# Non operating Substations
NET 1	86	54	9	22	1
NET 2	91	47	11	33	0
NET 3	23	7	4	8	4
NET 4	49	28	9	12	0
NET 5	11	4	2	5	0
NET 6	65	40	7	18	0
Total	325	180	42	98	5

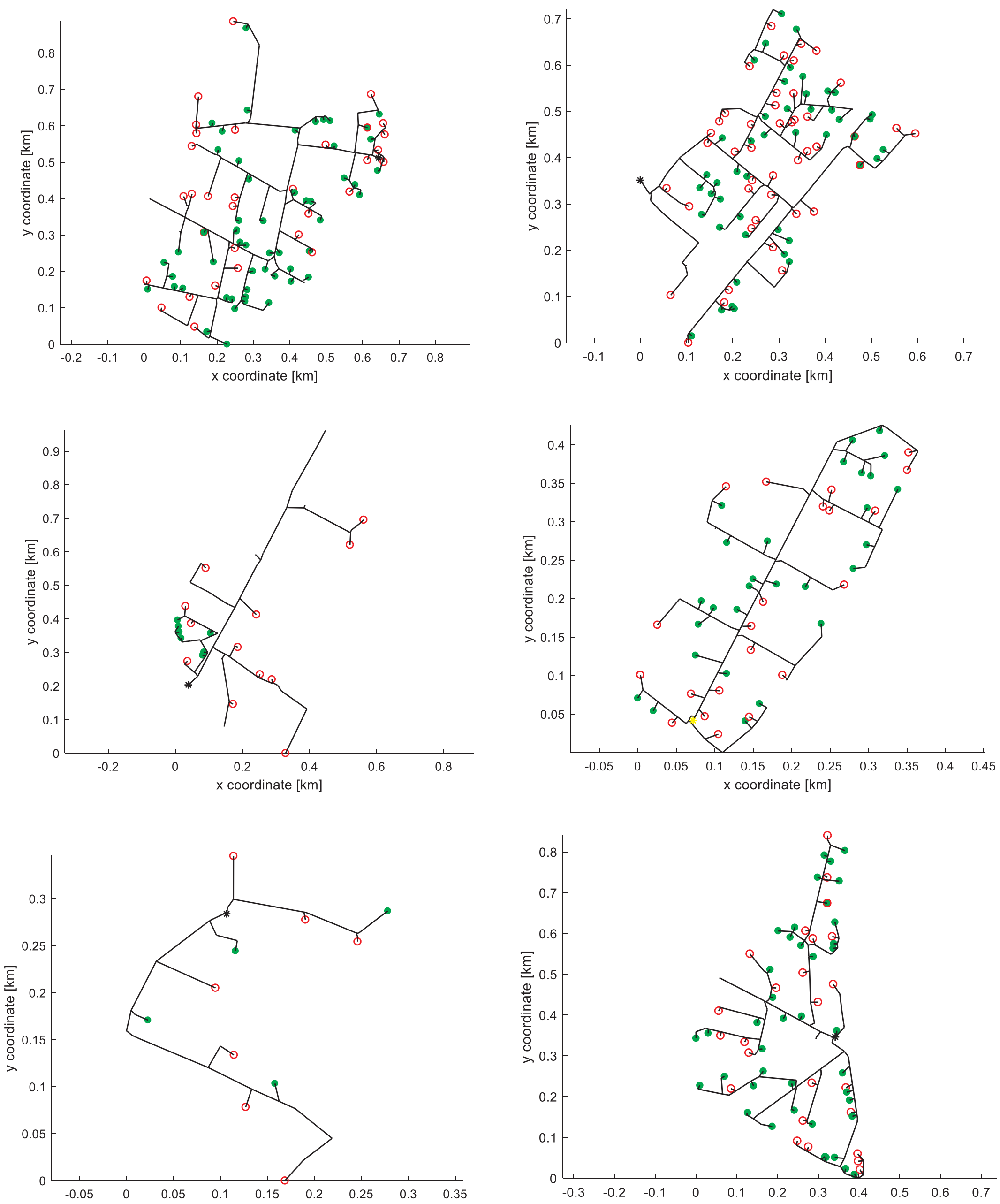

Fig. 6. Outcome of the field test: green = clean heat exchanger, red = possible presence of fouling/ insufficient data availability.

This is due to the fact that some gaps may occur between the data recorded for communication error, or some meters stop working for a while. In the specific day of the analysis, 5 substations were not operating, therefore no information is displayed. When a sufficient number of values for the evaluation is available, the tool is able to automatically detect the problem and highlight it. Concerning the fouling detection, almost 13% of the analysed buildings (42) are characterized by non-perfectly clean conditions, while for two substations the fouling level evaluated is high.

For each substation marked in red in Fig. 6, the tool if there are sufficient data in order to perform a reliable analysis and, in case, the current fouling level. The tool also provides historical information, showing the diagnosis results performed the previous days, weeks and months.

5.4. Effects of detection and cleaning on DH system efficiency

Malfunctions make heat exchangers less effective, which means that to exchange a defined heat flux, a larger mass flow rate is requested and the temperature difference on the primary side (inlet – outlet) is reduced. This involves two negative effects: (1) a larger water mass flow rate circulates and thus a larger amount of electricity must be spent for pumping; (2) the efficiency of thermal plants generally reduces. Malfunctions do not have a direct effect on the energy exchanged at the heat exchangers, unless the building demand is so large that the fouled heat exchanger is not able to exchange it. This is clearly shown in Fig. 4, where it is shown that the maximum heat flux in the case of clean or fouled conditions is similar. As a consequence, energy is not a suitable quantity to quantify the impact of malfunctions, as it could be only used in very cold days.

In order to experimentally evaluate the effects of the heat exchanger cleaning, the primary energy consumption at the plants before and after cleaning should be measured. Nevertheless, is not straightforward, mainly due to three issues: 1) the result depends on the operating plants, which might vary during operation; 2) in some cases evaluation of primary energy consumption is difficult. This is the case for instance when waste heat or renewable energy sources are used. When heat is produced through cogeneration plants, the evaluation of additional primary energy associated to heat production might be difficult, due to the fact that electricity production generally varies as well. For this reasons, in this paper the exergy flux supplied to the primary side of the heat exchanger, before and after cleaning, is considered as the evaluation of the global effects of fouling. Exergy is defined as the maximum work which can be extracted from an energy source when it completely used in a device (an ideal device) which only interacts with the external environment (see for example [40]). Alternatively, exergy can be intended as the minimum work which is necessary to obtain that energy source (with the same characteristics) starting from the environment and only interacting with the environment. When applied to the thermal energy flow supplied to a building in a heat exchanger, exergy provides an evaluation of the theoretical minimum work required in the thermal plants to supply heating to the substation in the considered conditions. In this case, the exergy flow is calculated as:

$$Gb = G\bullet[(h_s - h_r) - T_{env}(s_s - s_r)] = G\bullet c_p\left[(T_s - T_r) - T_{env}ln\left(\frac{T_s}{T_r}\right)\right] \tag{4}$$

where G is the water mass glow rate, h the enthalpy, s the entropy and T_{env} the environmental temperature; subscripts refer to the supply (s) and return (s) flows. The expression on the right side considers liquid as an incompressible fluid and neglects the effects of pressure drops, which contribution is actually minor. If fouling occurs in a heat exchanger, the amount of energy supplied remains the same as in clean conditions, but the return temperature on the primary side (T_r) increases. A larger water mass flow rate is also required in the network to supply the same heat load, as the temperature difference between supply and return reduces. On the basis of Eq. (4), the exergy associated with the same amount of energy increases. When considering an ideal energy conversion system, which produces work from fuel, it is possible to directly relate the increased work production (i.e. the exergy produced by the plant) with the increase in the fuel consumption.

Exergy is thus a common basis, which can be used to relate fouling with the additional fuel consumption without considering any specific production technology. In order to show the significance of this concept, the cogeneration plants installed in the Turin district heating system are considered. These are three combined cycles able to produce 1168 MW of electricity when operating in full electricity mode and 1002 MW of electricity and 760 MW of thermal energy when operating in full cogeneration mode (thermal energy refers to the nominal condition for the district heating network, i.e. when the supply temperature is 120 °C and the return network is 65 °C). The ratio between the non-produced electricity and the produced thermal energy can be evaluated as:

$$\frac{W_{el\_nonProd}}{\Phi_{prod}} = \frac{1168 - 1002}{760} = 0,22\frac{MW_{el}}{MW_{th}} \tag{5}$$

When the ratio between the exergy flux and the energy flux supplied to the network are calculated, considering the nominal values of supply (s) and return (r) temperatures, a quite similar result is obtained:

$$\frac{b}{\phi} = \frac{c_p\left[(T_s - T_r) - T_{env}ln\left(\frac{T_s}{T_r}\right)\right]}{c_p(T_s - T_r)} = 0,25\frac{MW_{el}}{MW_{th}} \tag{6}$$

where an environmental temperature (T_{env}) of 0 °C is considered in both evaluations. The fact that the two numbers are similar is embedded in

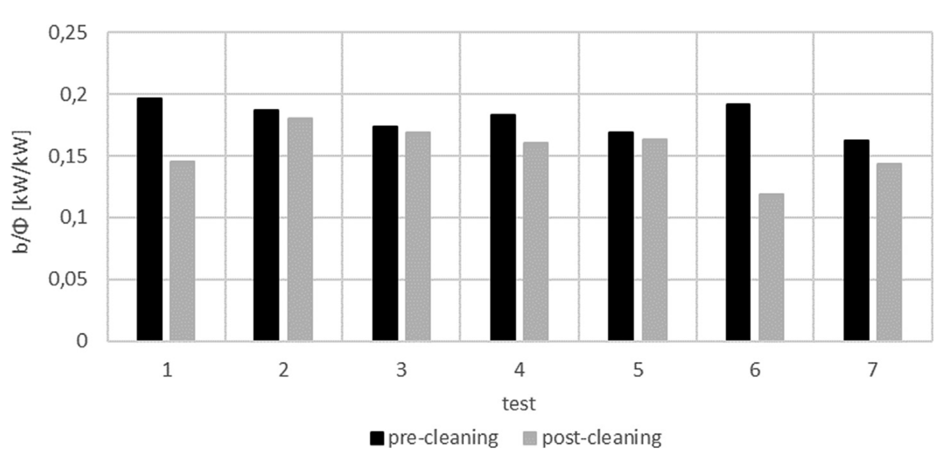

Fig. 7. Specific exergy spent before and after cleaning (experimental analysis).

the meaning of exergy: the production of a unit of exergy, independently of the type of energy (thermal, mechanical, electrical, chemical, etc.), requires the same amount of exergetic resource, in this case fuel. As a real plant is considered instead of an ideal plant causes the difference between the two numbers. Considering the results of equations (5) and (6), it is possible to consider the exergetic efficiency of the plant as constant, independently of the production mode (full electricity production, full cogeneration production, or intermediate modes). In particular, the electrical efficiency of the specific cogeneration system is 59%. It is thus possible to assume that the production of a unit of exergy (electrical or thermal) requires 1/0.59 units of fuel.

The reasons for using exergy instead of the number obtained from the ratio between non-produced electricity and thermal energy, are twofold:

(1) the latter is only available when nominal conditions are considered; when the return temperature increases, the heat transfer in the cogeneration heat exchanger reduces and the aforementioned ratio increases;
(2) exergy allows one to take into account the effect of a larger return temperature and does not depend on a specific heat production technology.

The analysis is applied here to 7 heat exchangers which have been cleaned or substituted. The ratio between the exergy flux and the heat flux exchanged is evaluated for each day of the heating season and the mean value is plotted in Fig. 7 for each case. This allows one removing the dependence on the characteristic daily demand. In fact, it should be noticed that when the demand of a building reduces, the operating temperatures change (mainly the temperature of water supplied to the heating devices on the secondary side, T_3, and the return temperature on the primary side, T_2), therefore also the exergy associated to a unit energy flow changes.. The exergy lost due to fouling is equivalent to the exergy flux that can be saved through detection and cleaning of the heat exchangers. The calculation can be performed by using Eq. (7):

$$\frac{\Delta b}{\phi} = \left[\left(\frac{b}{\phi}\right)_{post} - \left(\frac{b}{\phi}\right)_{pre}\right] \tag{7}$$

Results show that fouling removal increases the exergy performances significantly: the average reduction in exergy use is about 14%, but in some cases it is higher than 20%.

The total impact of fouling can be analyzed considering the annual operating conditions and the configuration of thermal plants. The annual thermal demand is about 1930 GWh, plus about 230 GWh of heat losses (estimated). On the basis of the heat duration curve, 95% of the total annual load (i.e. 2070 GWh) is covered by cogeneration plants, also thanks to the use of thermal storage tanks. The remaining load (about 86 GWh) is covered with boilers.

As already discussed, fouling does not affect the thermal demand of buildings, but the temperature level of water returning to the thermal plants. The efficiency of boilers (about 90%) is not particularly affected by this change, while the thermal efficiency of cogeneration plants is (exergy efficiency can be considered as constant, on the basis of the considerations previously made, but due to the larger exergy content of the thermal production, also the amount of fuel consumption increases). Without fouling, it can be considered that 2070 GWh of heat corresponds to about 518 GWh of exergy (equation (6)), which production requires about 879 GWh of fuel (the plant exergetic efficiency is 59%). When fouling is considered affecting 13% of the substations, their average exergy consumption increases of about 14%, therefore the exergy associated with the heat to be produced by cogeneration plants increases to about 528 GWh (the electricity production capacity reduces correspondingly). The total fuel consumption, including 96 GWh of fuel burned in boilers, thus increases of about 1.6%, from about 975 GWh to 991 GWh.

6. Conclusions

Automatic detection of fouling in heat exchanger substations is one of the various issues that enables district heating systems to become more and more efficient. This issue is particularly important in the case of low temperature district heating.

This paper proposes a tool for the automatic detection of fouling in large heat exchanger networks. The main strengths of the proposed approach, which make this tool general and suitable for all types of district heating networks, are:

1. No information is required about the heat exchanger geometry, type and dimension (the lack of such information is typical of large district heating networks which involve a huge number of heat exchangers, often installed in different periods). This also means that no detailed models of the heat exchangers are necessary in order to fully capture their configuration.
2. It does not require measurements of pressure drops.
3. The requested data are gathered from metering equipment, which measure mass flow rate and temperatures. Meters are often installed in building substations for billing purpose.
4. Time transient data are collected from the metering equipment with proper frequency, e.g. each five minutes. An automatic pre-processing is performed to re-organize the data in a suitable form.

The last point implies the presence of a tool for automatic evaluation of a time-frame when the system works in quasi-steady state conditions (i.e. when the thermal request is affected by small oscillations).

Possible variations of the product UAF (overall heat transfer coefficient times area times the correction factor) are used for detecting the presence of fouling. In particular the fitting curve associated with the relation between UAF and the heat flux is used in order to detect the fouled heat exchangers without falling into false alarms. The approach has been validated by means of experimental data. The outcomes of the tests show that the methodology allows to successfully detect variation in fouling conditions.

A software has been developed, based on the described methodology and it has been applied to the substations of some distribution networks in the Turin district heating system. In particular, a graphical output is provided in order to automatically visualize the operating conditions of 325 heat exchangers. This can be automatically applied to several distribution networks. The simple and clear interface, make the proposed software particularly suitable for assisting the exchanger operators to plan the cleaning schedules and thus allows the district heating system to operate efficiently. In fact, also when applied to various distribution networks it is easy visualizing the entire result.

Results also investigate the effects of detection and cleaning of the fouled heat exchangers in terms of primary energy. The relevance of this kind of tool is highlighted by the result of primary energy that can be saved by cleaning fouled heat exchangers. About 1.6% of the primary energy annually consumed in the entire network can be saved by cleaning all the fouled heat exchangers. This result suggests that fouling monitoring is an important aspect in order to keep the efficiency of the network high.

Declaration of Competing Interest

None.

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