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Heat recovery from urban wastewater: analysis of the variability of flow rate and temperature in the sewer of Bologna, Italy

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Abstract

Domestic wastewater were characterize by higher temperature because inside the buildings 60% of the water was heated by showers, tubs, sinks, dishwashers and clothes washers. This heat, nowadays lost into the sewer system, could be make the wastewater a carrier of heat. This heat can be reused, for the production of clean and regenerable thermal energy, through heat exchangers and heat pumps, for the conditioning and heating of buildings. There are several options to recover this heat embedded in the wastewater: within houses (small scale applications), from the sewer (medium scale applications), or at wastewater treatment plants (large scale applications). In this paper results of a monitoring period of six months in the sewer system of Bologna (Italy) have showed the variability of wastewater flow rate and temperature and their daily trend. The trend of the flow (ratio between the hourly flow and the medium daily flow) for the generic day is linked with the population, with coefficients that are in the range of 0.25 - 1.50 with peak values ranging between 1.30 and 1.50; the trend of the sewage temperature for the generic day has coefficients in a range between 0.90 and 1.05, and it is independent by the population. The amount of thermal energy that can be obtained from wastewater and the optimally design of heat recovery systems depend on knowledge of the flow rate and wastewater temperature. This study can be useful to map the potential thermal energy of sewage systems and to design the heat recovery systems.

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Nomenclature*Symbols*

COP	coefficient of performance
T	temperature [$^{\circ}C$]
V	flow rate [l/s]
A	heat exchange area [m^2]
\dot{Q}	thermal power [kW]
cp	specific heat capacity as 4.186 [kJ/kg $^{\circ}K$]
ρ	density [as 1 kg/l]
ΔT	temperature drop [$^{\circ}K$]
L	pipes length [m]
N	pipes number
d_i	pipe diameter
K	heat transfer coefficient [$W/m^2 \text{ } ^{\circ}K$]
\dot{L}	required external work [kW]

Indexes

inp	input value
out	output value
w	wastewater
F	fluid
B	building

1. Introduction

Space heating and cooling and domestic hot water supply represent the biggest share of energy in residential buildings [1]. There are number of uses of hot water in buildings, including showers, tubs, sinks, dishwashers and clothes washers. In virtually all of these cleaning applications, the wastewater retains a significant portion of its initial energy that could be recovered and used every day.

In the world, with finite natural resources and large energy demands, it becomes ever increasingly important to understand the mechanisms that degrade energy and resources and to develop systematic approaches for improving systems and, thus, also reducing the impact on the environment [2].

Buildings are responsible for two thirds of total electricity consumption and one third of greenhouse gas emissions [3]. More recently, the data analysis from residential and commercial agglomerations has shown that over half of global emissions of greenhouse gases are generated from the building sector [4]. For example, about 23% of the gas demand of households in the Netherlands is used for heating water [5]. This fact provides a fundamental and substantial reason for reducing such energy consumption, since in doing so the resulting emissions will also decrease. Warm water conservation is thus an important measure to reduce greenhouse gas emissions from households [2, 3, 4, 5, 6].

Furthermore, it should be underlined that in recent years the energy performance of buildings has definitely improved, at least as far as new construction are concerned. However, past studies have focused almost exclusively on the heating and cooling systems and have neglected other aspects such as those linked to water use [7]. Studies made in Swiss [6] showed that 15% of the thermal energy supplied to buildings is lost through the sewer system; this value rises up to 30% in well-insulated buildings with low consumption. This leads to the fact that, today, sewers represent the largest source of heat losses in buildings [6]. Hot water is still discharged into the sewer system making the domestic wastewater a carrier of heat [5].

In many countries technicians and engineers are trying to recover the hydrothermal energy from wastewater through the aid of plant (whose main elements are the heat exchangers and heat pumps) [3, 4, 5, 6, 7, 8, 9, 10, 11, 12, 13, 14, 15] that allow the air conditioning of buildings.

In light of these observations would be appropriate revisit the concept of wastewater, not only as a waste, but as a source of thermal energy regenerable and clean that it can be reused for the cooling and heating of buildings [4].

There are several options to recover this heat embedded in water. The heat content of water from households can be recovered within houses (small scale applications), from the sewer (medium scale applications), or at wastewater treatment plants (large scale applications) [5].

It is from about 30 years that plants, for the recovery of heat from wastewater, were installed in different part of the world. In 1987, the manager company of the waste water treatment plant (WWTP) of the Metropolitan city of Tokyo built the first heat recovery plant, which uses the heat of the water coming out of the Ochiai WWTP to conditioning the administrative offices [15].

In 1993, the Swiss Federal Office of Energy awarded the Swiss Energy Agency for Infrastructure Plants the task of developing and propagating the use of wastewater as a source of heating and cooling for buildings. As a result of activities of this program, Switzerland has taken on the role as a pioneer in the international field of wastewater heat recovery [6].

Recently in China, these technologies were inserted in modern buildings such as the train station in Beijing, opened in 2008. In Vancouver, Canada, in 2010 the first system of heat recovery from sewage in North America was implemented and, in May 2012, the first plant, able to heat 60 stacked urban townhomes called "Seven 35" was inaugurated. The heat recovery from wastewater is also widespread in Europe, they are good example the installations located in the WWTPs of Oslo and Zurich [6].

2. System overview

The essential elements that form a heat recovery system are the heat exchanger and the heat pump [1]. The key problem of this system is finding an optimal design and specification for the sewage heat exchanger, that are devices that facilitate the exchange of heat between two fluids at different temperature without exposing them to a direct contact. In general, the heat exchangers currently used can be grouped into two types: indirect and direct. The indirect-type (wastewater to circulating water) heat exchangers included plate heat exchanger and shell-and-tube heat exchanger. The direct-type (wastewater to refrigerant) heat exchangers can be further grouped into two categories: flooded and dry-expansion evaporators [9]. The heat exchangers can be also classified on several criteria including: the heat exchange process, the ratio between the exchange surface and the volume, the configurations of the motion of fluids, the geometry and the prevailing mechanism of heat transmission.

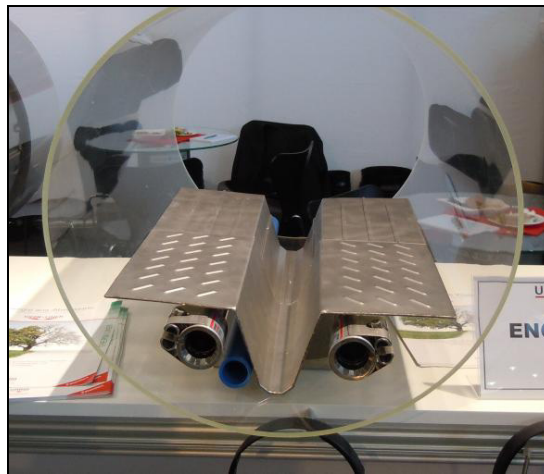


Fig. 1. Example of direct heat exchanger (Uhrig Therm-Liner) that could be installed on the bottom of the sewer conduit.

The design parameters of these systems are: the flow rate and the temperature of wastewater, the temperature difference of the wastewater upstream and downstream of the heat exchanger, the geometry of the pipe and of the

heat exchanger, the viscosity of the wastewater, the velocity of the fluids in the heat exchanger, the fouling resistance caused by the formation of biofilm, the heat exchange coefficient and the heat transfer surface.

The main problem that involves when the heat exchangers are installed in the sewage pipe is the formation of biofilm on the wall of the heat exchanger [2]. The biofilm leads to a reduction of the efficiency of the heat exchange. In order to overcome this problem many exchangers are designed with an oversize surface of heat exchange to compensate for the reduced coefficient heat transfer.

The other essential element, in a heat recovery system, is the heat pump [8]. It is characterized by a coefficient of performance (COP) which is the number of units of energy delivered to the hot reservoir per unit work input. The value of the COP increases when the temperature difference between the two sources decreases; in [16] the authors highlight that if the temperature of the wastewater is about 10°C, the COP ranges from 3.25 to 3.5; if the temperature increase also the value of the COP increase, in particular the value of the COP increases of about 0.3 every + 2°C.

Independently on the type of technology used, in order to correctly design the equipments, it is essential to have reliable information as regards the wastewater flows and its temperatures, in fact these parameters will obviously affect the performance of the system and the related costs. Another point to emphasize is that flow into sewers is related to the variability of water demand by users. The flow has a cyclical daily and weekly trend, which is different on working days or at weekends [17]. Such variations are therefore influenced by the climatic conditions, work activities and the habits of the users. It is also important to understand how temperature changes within the wastewater collectors; usually this aspect is neglected in traditional research on sewer systems.

3. Case study

Usually the modeling of wastewater heat recovery presents several obstacles. First, appropriate input data has to be generated or acquired based on highly variable water usage statistics. Because wastewater heat is almost never considered, there are very few statistics available for wastewater temperature data. In order to implement data related to flow rate and temperature of the wastewater has been analyzed and monitored the sewer system of city of Bologna.



Fig. 2. Location of the measurement points with highlighted the upstream drained area for each point. The point "E" include the whole sewer system and in that point is located the wastewater treatment plan.

The dataset used in this work was collected by HERA, manager of the sewer system in Bologna, from October 2005 until March 2006. During this monitoring period various area-velocity measuring stations were installed, which provided data concerning flow, level, speed and temperature of the wastewater. The flow and temperature variations in the wastewater were analyzed at all the measuring stations of Figure 2.

The characteristics of the conduits in which the sensor were installed are shown in Table 1. It should be noted that the sewer is combined and therefore during the rainfall events the wastewater is mixed with stormwater.

Table 1. Characteristics of the monitored conduits

Point of measurement	Geometry	Material	Height (m)	Width (m)	Invert level (m)
A	Polycentric	Reinforced Conc.	1.92	2.40	5.65
B	Polycentric	Brick	3.00	4.00	3.97
C	Polycentric	Brick	2.24	2.80	4.84
D	Polycentric	Brick	3.00	4.00	4.33
E	Polycentric	Brick	2.24	2.80	6.65

Table 2. Characteristics of the monitored conduits in terms of drained area, total length of conduits, longest path, residents population.

Point of measurement	Drained Area (ha)	Total length (m)	Longest path (m)	Inhabitants
A	276	24'870	6'310	12'212
B	533	76'740	8'640	57'631
C	665	100'810	7'340	73'660
D	1'151	169'300	12'930	129'862
E	5'522	727'000	18'550	440'795

3.1. Data analysis

The data, recorded every 3 minutes, were averaged with a time step of one hour. The data recorded, in order to eliminate possible malfunction of the instruments, have been treated through a selection process based on the moving average. Figure 3 shows the time series for the month of October, for the three monitored parameters: flow, wastewater temperature and external temperature (air temperature), for the conduit "C", in order to identify the dynamics over time.

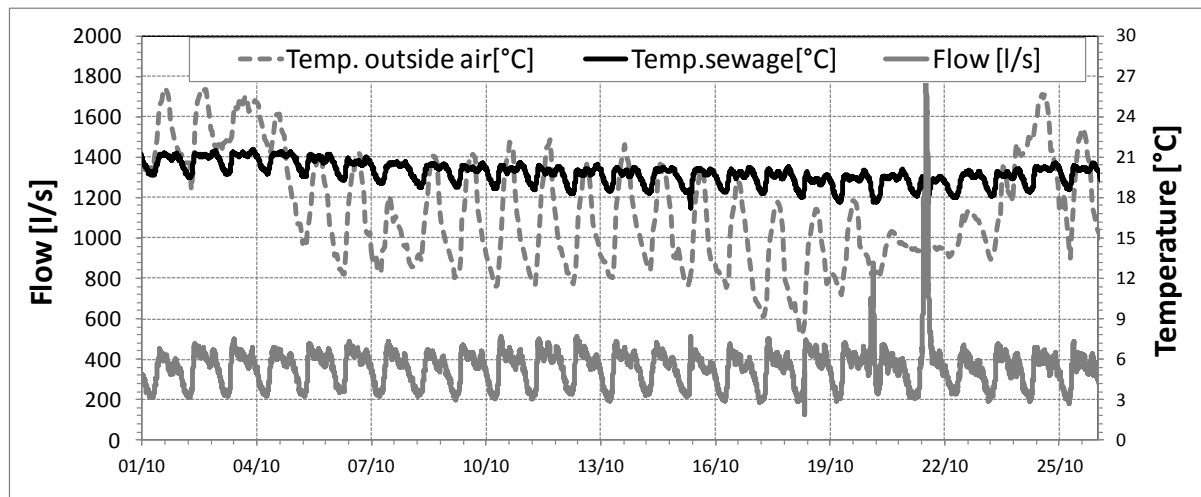


Fig. 3. Representation of the trend of outside air temperature, sewage temperature and flow (hourly average) recorded in the conduit "C" in the month of October.

Flow and wastewater temperature show a trend almost constant; the periodic daily fluctuations are visible clearly. It is evident that the temperature variations in the wastewater are more affected by variations in flow rate rather than by the variations of outside air temperature. During rainfall events, since the sewer is combined, there is an increase in flow rate and to a consequent decrease in wastewater temperature.

Analyzing the temperature data of the wastewater during the whole period of observation available it is possible to ascertain its variability in relation to the outdoor air temperature. Figure 4 shows that the wastewater temperature in sewer system, compared to outside air temperature, is relatively stable in the observation time.

The wastewater temperature is 11-16°C in winter, which is higher than air temperature; in particular, the minimum temperature of the wastewater was recorded between the end of December and the beginning of January when the air temperature drops to values of about -2.5°C while the temperature of wastewater is always above 11°C.

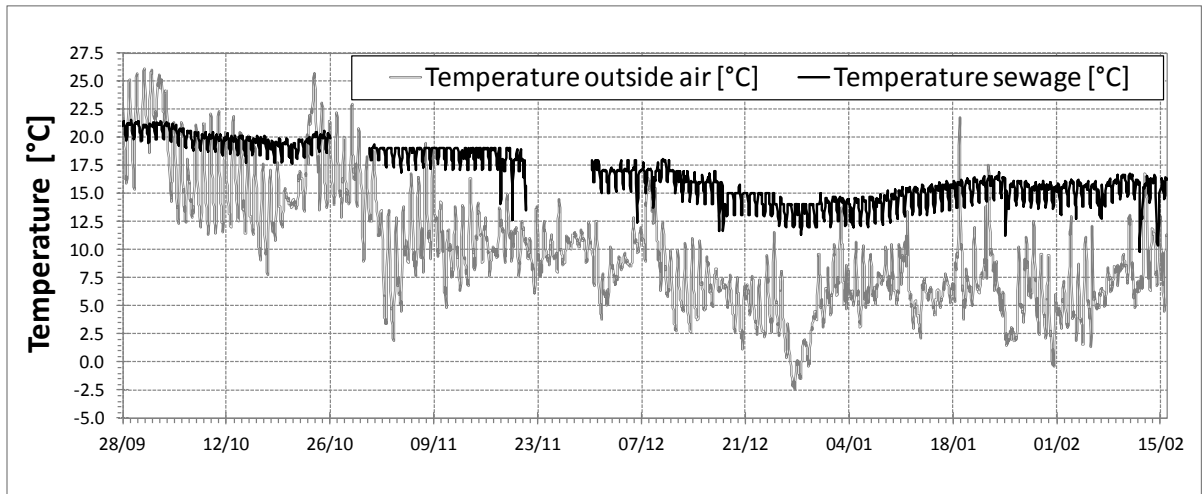


Fig. 4. Time series recorded from 28/09/2006 to 15/02/2007 in the conduit "C" of the hourly average temperature of the sewage and of the outside air.

Figure 5 shows the variation of flow rate (on the left) and temperature (on the right) of wastewater. In particular for each hours of the day (considering the whole observation period), the figure shows the first and third quartile (gray area) and the median (dots) for each measurement points. In the figure is possible to observe the characteristic variation of the flow as a function of consumer habits; the flow values, in each point of measure, depend on the number of inhabitants in the catchment drained by sewer system and therefore the variations are very significant, while temperatures have daily fluctuations in the order of 2-3°C for almost all conduits. The excursions of temperature are minimal even during the day, in fact, generally are not higher than 20%.

At night, with low water consumption, the temperatures are typically from 2°C to 4°C lower than during the day. The variations during the weeks can be attributed to the weather influence: water temperature is equal to about 10-14°C in winter, to about 14-18°C in spring/autumn and to about 18-22°C in summer.

During rainy periods, the wastewater temperature normally drops by a few degrees. This only applies, however, to combined sewer systems.

Such behavior is more evident in Figures 6 and 7, which show the daily peak coefficients evaluated for both the flow rate and for the sewage temperature. The hourly coefficient of the average day was obtained through the ratio between the flow/temperature hourly average and the flow/temperature daily average. Daily changes are determined by the varying ratio of water consumption.

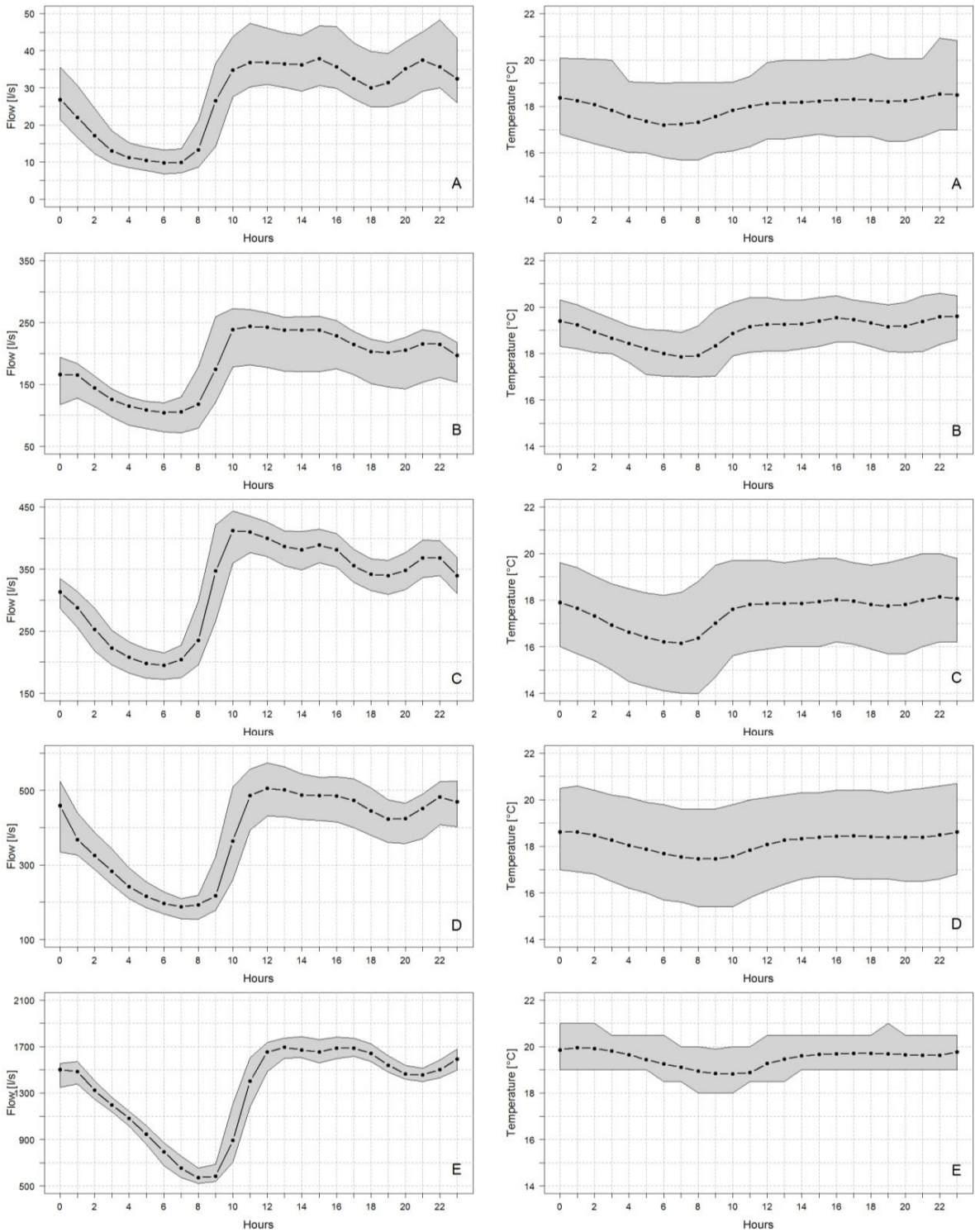


Fig. 5. Variation of flow rate (on the left) and temperature (on the right) of wastewater for conduit C considering the whole observation period; gray area represents the first and third quartile and dots are the median.

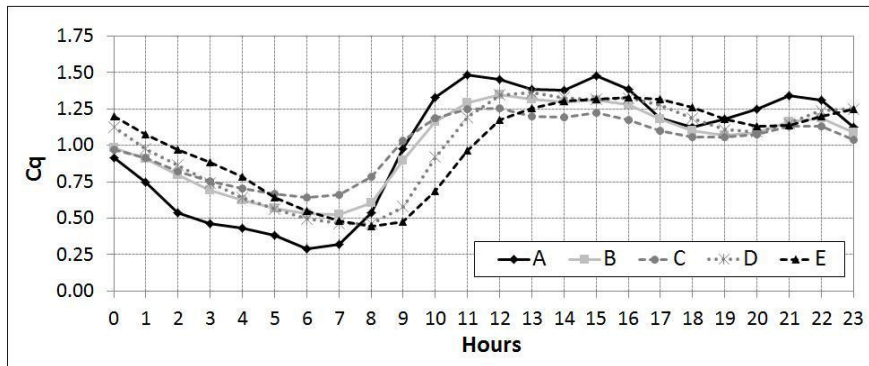


Fig. 6. Average hourly value of the flow coefficients in the month of December for the five measurement points.

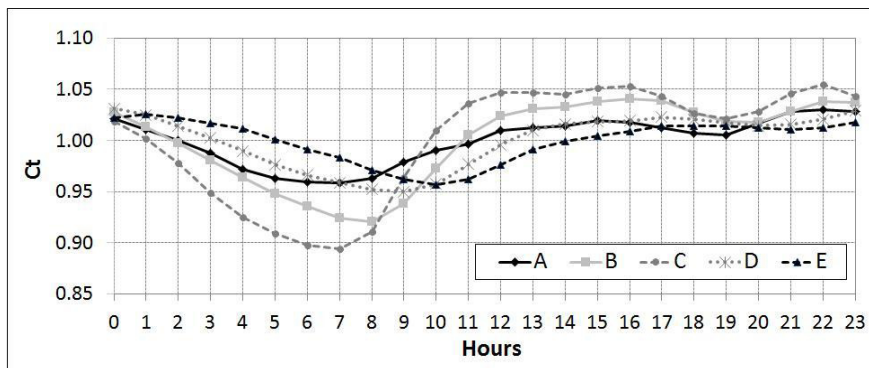


Fig. 7. Average hourly value of the sewage temperature coefficients in the month of January for the five measurement points.

3.2. Example of calculation

The design of a system for the recovery of the wastewater heat and its use in the building requires the dimensioning of its two basic elements: the heat exchanger and the heat pump. In this paragraph it is reported an example of calculation for a generic heat exchanger and the heat pump. The input data, needed for the design of the system, are derived from statistical analysis performed for the sewerage system of Bologna.

The working principle is the following: during the winter the wastewater heat exchanger takes the heat from the urban sewage filtered through filth block device (to reduce the corrosion and extend the service life of the wastewater heat exchanger), and sends it to the evaporator side of the heat pump as a low grade heat source. The compression heat pump system releases the heat at the condenser side and sends the heat to the heat supplying system [20].

The system design starts setting the temperature in input (T_i) and in output (T_u) and the flow rate (V_F). The problem consists in the choice of an appropriate heat exchanger and in its dimensioning, i.e. in the assessment of the area of the heat exchange (A_S). The thermal power transferred from the wastewater (\dot{Q}_F) through the heat exchanger to the heat transfer fluid is determined by the equation of heat balance:

$$\dot{Q}_F = \Delta T_W \cdot c_w \cdot \rho_w \cdot V_F \quad (1)$$

The above formula shows that to increase the available power must increase the flow rate or the temperature drop. In this example has been assumed that the available wastewater flow rate is about 2 l/s, (medium flow rate

generated from about 800-1000 inhabitants). The water will enter into the heat exchanger at a temperature of 14.9°C and will come out at a temperature of 8°C, the temperature drop will be equal to 6.9°C. The obtainable thermal power from the wastewater appears to be 58 kW, with it, using the following formula it is estimated the heat exchange surface in a shell heat exchanger [21].

$$\dot{Q}_F = k \cdot A_s \cdot \Delta T_m = k \cdot L \cdot N \cdot \pi \cdot d_i \cdot \quad (2)$$

The heat transfer coefficient adopted for wastewater with organic origin is equal to 850 [W/m² °K] as measured by Schilperoort et al. [18]. The obtained heat exchange area is equal to 9.9 m²; in favor of safety, the area will be increased of 50% to take into account of the efficiency reduction due to the formation of biofilm [9], obtaining in this way an heat exchange area equal to 14,75 m². If will be adopted pipes with a length of 3 meters and with a diameter of 20 mm, 78 pipes will be needed inside of the shell and tube heat exchange [21].

The power transferred from the heat pump to the heating and production of sanitary hot water is equal to the sum of the thermal power obtainable from the heat transfer fluid with the external work to be supplied to the heat pump by means of electricity.

$$\dot{Q}_B = \dot{Q}_F + \dot{L} \quad (3)$$

If, as recommended by Qian et al. [16], will be adopted a COP = 4; the required work is 19 kW and the thermal power transferred to the building is 77 kW, corresponding to about 674 MWh/year.

4. Conclusions

This paper has analyzed the daily and seasonal variability of flow and temperature of wastewater in the sewer system of Bologna. This kind of study can be useful in the design of heat recovery systems that need the knowledge of temperature trends. In particular has been shown that the flow trend varies according to the size of the sewer system with peak values of the daily coefficient between 1.50 and 1.25 from about 12,000 to over 400,000 inhabitants. The minimum values of the daily coefficient are included between 0.25 and 0.50. The wastewater temperature shows instead a daily variability most limited with variation coefficients between 0.90 and 1.05.

In the second part of the paper has been executed an example of dimensioning of a system that exploits wastewater highlighting the values that the various parameters may assume in this type of calculation.

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