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PI-based cascade control for Fresnel solar collectors in wastewater reclamation

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Abstract: This work presents a novel demonstration-scale integration of a 36-m^2 Fresnel solar collector in urban wastewater reclamation. A prototype plant was designed and installed to study *Escherichia coli* and total coliforms disinfection in continuous flow mode. The plant modelling was empirically addressed, resulting in different linear first-order models, which were used to design a PI-based cascade control approach for the automatic operation of the photoreactor. Considering EU 2020/741 Regulation, water quality Class D and Class A were achieved when operating the upgraded design of the plant at 50 °C (200 L/h) and 60 ° C (150 L/h), respectively.

Keywords: Process Control, PID Control, Cascade Control, Disturbance Rejection, Solar Concentration, Renewable Energy, Water Disinfection.

1. INTRODUCTION

Sustainable and efficient water management has become an imperative in modern society, especially in urban environments where increasing demand and scarcity of water resources are growing challenges. Population growth and urban development impose significant pressure on water supply systems, simultaneously leading to an increase in wastewater effluent volumes. In this context, urban wastewater reclamation emerges as an innovative and sustainable solution, providing a holistic and responsible approach to address water management. Nevertheless, minimum reclaimed water quality standards must be achieved according to EU 2020/741 Regulation, ensuring its reuse with all the guarantees of public health and environmental sustainability. This European regulation is mandatory from June 2023 and defines different water qualities (Class A, B, C and D) depending on its final use. The reduction in the limits associated to microbiological indicators (such as *Escherichia coli*) and the new monitoring requirements, are forcing Wastewater Treatment Plants (WWTPs) to upgrade their facilities by integrating new technologies (Truchado et *al*., 2021). Conventional wastewater reclamation processes are usually based on a combination of membrane filtration technology, ozonisation, chlorination and/or UV light disinfection (Englande and Krenkel, 2003). Nevertheless, the use of these technologies involves high energy and chemical consumption, so that new cost-effective technologies are needed to boost wastewater reuse. Therefore, urban wastewater reclamation is open to the research and development of new or enhanced cost-effective technologies, being the use of renewable energy sources, such as solar energy, a good alternative to simultaneously reduce operating costs and mitigate treatment carbon footprint. In this regard, the integration of solar concentration technology in urban wastewater reclamation may play a key role. Concentrated solar power technology is based on the use of mirrors or lenses to focus large amounts of sunlight onto a specific area, resulting in high-energy concentration. This approach offers a variety of industrial applications such as electric power generation, water desalination and heating steam production, among others (Sonawane and Raja, 2017). These are just some common application examples, as solar concentration is still being researched and developed to explore new applications and improve the efficiency of existing ones. Its versatility and capacity to generate high operating temperatures offer a potential technology to address several energy and environmental needs, such as wastewater reclamation. As far as authors know, there is no previous work on the use of Fresnel-type solar concentration technology for urban wastewater reclamation and let alone at demonstration scale. Non-conventional applications of this technology in water treatment are mainly focused on drinking water production through solar water disinfection (SODIS) in continuous flow mode at pilot scale, using tap or distillate water (Chaúque et *al*., 2023). Therefore, the goal of this work is to integrate, for the first time, Fresnel-type solar concentration technology in urban wastewater reclamation. To this aim, a prototype plant based on a 36-m^2 Fresnel solar collector was designed, automated and experimentally evaluated for actual reclamation of secondary effluent from *El Bobar* WWTP (Almería, Spain).

This work presents preliminary results of a cascade control approach based on PI controllers to regulate Fresnel outlet temperature. Real experimental were perform on actual facility demonstrating an adequate performance of the proposed control scheme. Note that the control approach proposed in this paper is widely known. The main contribution is the implementation of this technique to a novel wastewater reclamation treatment, with the aim of boosting its commercial scale-up.

2. DEMONSTRATION PLANT DESCRIPTION

The demonstration plant is based on a 36-m^2 lineal Fresnel collector that concentrates incident solar irradiance into a 6.5-cm diameter borosilicate tube (solar concentration factor equal to ~ 32). The solar collector system is composed of 10 mirrors 6-m long and 0.44-m width, being installed the borosilicate tube 3.5 m height above them and covered by an U-shape secondary concentrator. This module (Module FLT20) was provided and installed by SOLATOM (Valencia, Spain) in *El Bobar* WWTP (Almería, Spain) in a north-south orientation (Fig. 1). Individual solar tracking for each of the 10 axis was programmed based on the solar collector geolocation and orientation. Note that the commercial available version of Module FLT20 is based on a vacuum absorber tube, as steam generation through solar thermal energy is usually the target of the process. Technical specifications of this module can be consulted on the manufacturer's official website (https://solatom.com/index/tecnologia/). The solar Fresnel collector was connected to a 5-m^3 storage tank being the secondary effluent pumped to the photo-reactor through a 1-kW self-priming centrifugal pump (MODEL JPG 1000 HIDROBEX). A shell and tube heat exchanger (MODEL HRS K 7 79/18) was implemented as an energy recovery stage to simultaneously achieve inlet water pre-heating and outlet water-cooling. Regarding instrumentation, a proportional electrovalve (MODEL 2025V 30 04 GENEBRE) and ultrasonic flowmeter (MODEL flowTRANS US W01 JUMO) were installed to address the photoreactor control and automation. Four PT100 probes were used to monitor the temperature of the water at different points of the plant.

Fig. 1. Demonstration plant based on Fresnel-type solar concentration technology (*El Bobar* WWTP, Almería, Spain).

Solar irradiance (I_{solar}) monitoring was achieved using a pyranometer (MODEL LPPYRA03AC) supplied by Delta Ohm, being the spectral range 300-2800 nm. A schematic description of the plant is shown in Fig. 2. Note that the plant control and monitoring system was programmed in a SCADA using DAQFactory® software.

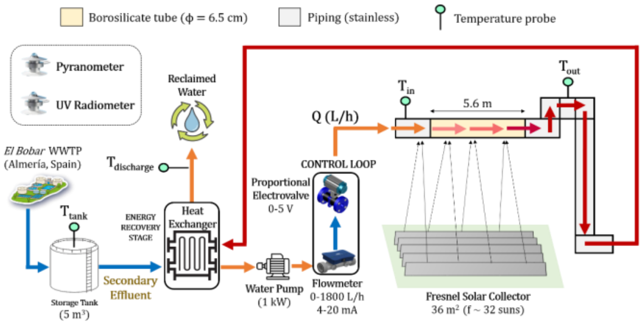

Fig. 2. Demonstration plant scheme.

3. PROBLEM STATEMENT

The plant under study was designed to remove pathogens contained in the wastewater through the simultaneous effect of temperature and UV irradiance. Fresnel outlet temperature (T_{out}) mainly determines reclaimed water quality, being the main variable to control throughout the operation. To this end, the plant incorporates a proportional electrovalve to regulate inlet wastewater flow (Q) to the solar collector. Therefore, a classical cascade control approach was proposed. Note that T_{out} is strongly influenced by the environmental conditions: solar irradiance (I_{solar}), relative humidity (RH) and wind speed (WS). These parameters, together with the inlet wastewater temperature (T_{in}), are the main process disturbances from a control point of view (See Fig. 3).

4. CONTROL SYSTEM

This section summarizes the proposed cascade control approach (Fig. 3). The primary loop corresponds to the control of T_{out} by modifying Q, meanwhile the secondary loop controls Q through the voltage supplied to the proportional electrovalve. Note that the main purpose of these loops is disturbance rejection and setpoint tracking, respectively.

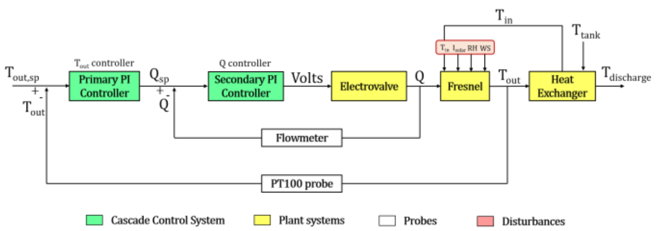

Fig. 3. Cascade control system scheme.

Control system design was conducted using the empirical modelling of the plant, obtained through the reaction curve method such as discussed below. Responses were successfully correlated to linear first-order models with time delay, so that the following characteristic parameters were estimated in each case: static gain (K), time constant (τ), and time delay (Θ). These linear models are commonly used in industry as most processes exhibit a damped dynamic response (Åström and Hägglund, 2006; Guzmán et *al*., 2023). The plant was operated with and without heat exchanger (energy recovery stage), resulting in different dynamic behaviours of the photoreactor. As a result, two first-order models were obtained for the solar collector for each plant configuration. It should be highlighted that the plant configuration does not affect the modelling of the proportional electrovalve so that a single first-order model was obtained for it. The parameters of the proportional electrovalve model (K, τ, and Θ) were computed by averaging those obtained by applying different step changes sizes and signs in the whole operating range (0-5 Volts). In this way, inherent non-linearities of the system (e.g. hysteresis) were addressed. Regarding the modelling of the Fresnel solar collector, step changes in the secondary effluent feed flow (Q) were conducted, monitoring the water temperature at the exit of the photoreactor (T_{out}) for each plant configuration (with and without incorporating a heat exchanger in the plant).

First, the secondary control loop was tuned based on the first-order linear model obtained for the proportional electrovalve. Afterwards, the secondary loop was set to automatic. Then, the dynamic response of the system was correlated to a first-order system by conducting a step change in wastewater feed flow setpoint (Q_{sp}). Finally, the primary loop was tuned considering the dynamic response of the system when the primary and secondary control loops are set to manual and automatic, respectively. Using previous control system tuning, a standard PI control action was obtained for the primary and secondary loop as shown in (1).

$$u_c(t) = K_p\left(e(t) + \frac{1}{T_i}\int_0^t e(\tau)d\tau\right) \qquad (1)$$

where $u_c(t)$ is the control signal, $e(t)$ is the error between the setpoint and the actual value of the process variable, and T_i and K_p correspond to the classical parameters of a PI controller (proportional gain and integral time, respectively).

The corresponding control parameters were tuned using Lambda method for first-order systems with time delay (Åström and Hägglund, 2006) (2).

$$K_p = \frac{\tau}{K(\lambda + \Theta)} \qquad T_i = \tau \qquad (2)$$

where λ is the desired closed-loop time constant.

Classical anti-windup (Åström and Hägglund, 2006) was implemented in both control loops (primary and secondary) to avoid excessive accumulative integration when saturated conditions are present in the system due to physical operating limits. Anti-windup tracking constant time (T_t) was computed as followed:

$$T_t = \sqrt{T_i} \qquad (3)$$

5. RESULTS AND DISCUSSION

The solar Fresnel collector was operated in continuous flow mode for two different plant configurations: with and without energy recovery stage (heat exchanger). Operating temperatures of 40, 50, 60, and 70 °C were studied for each configuration allowing water treatment capacity and bacteria inactivation comparison. The automatic operation of the process was evaluated by setting a specific operating temperature (primary control setpoint, $T_{out,sp}$) so that the cascade control system automatically modified water treatment capacity (Q) throughout the operation to compensate environmental disturbances (solar irradiance availability, water inlet temperature, humidity, wind speed…).

It is worth mentioning that a batch start-up of the control system is required, as the control system was designed to operate in the range of 40-70 °C. Adequate control results may not be obtained when operating the plant in a different scenario, as PI controllers should be tuned close to the target operating temperature.

5.1. Modelling

The averaged first-order model parameters corresponding to the modelling of the proportional electrovalve are shown in Table 1.

Table 1. Characteristic first-order parameters for the linear model of the proportional electrovalve.

Voltage vs Q (Input vs Output)	First-order model parameters (averaged)		
	Gain (K) [(L/h) / Volt]	Time constant (τ) (sec)	Time delay (Θ) (sec)
	572.6	2.3	2.4

The electrovalve presented a high non-linear behaviour when operating in the range of 0-1.5 Volts, significantly affecting the system gain (K). Regarding time delay (Θ) it is quite similar in all cases (2-3 sec). This is logical as the response time of the electrovalve is proportional to the voltage variation (1.5 sec/Volt) and it is not affected by the initial position of the valve. Therefore, the time constant (τ) of the system is strongly influenced by the magnitude of the voltage variation. Nevertheless, not only the magnitude but also the sign of the step change applied to the voltage affects the system response, as hysteresis of the electrovalve was observed. All these inherent characteristics of the system result in a K and τ dependence on the initial operating point (valve position) and the size and sign of the control action variation (voltage). It is also worth mentioning that voltage signals above 3.5 Volts result in saturation of the flowmeter (1800 L/h) as wastewater feed pump was oversized. Thus, the operating range of the proportional electrovalve was set to 0-3.5 Volts.

The solar collector modelling is shown in Table 2 for both plant configurations: with and without incorporating a heat exchanger as energy recovery stage. Characteristic first-order parameters were obtained for both plant configurations by applying similar step changes sizes in the control action (Q), close to the same final operating state (Q_f = 250 L/h). Hence, τ and Θ are very similar in both cases, as these parameters are related to fluid-dynamic aspects such as turbulence and water velocity, which are linked to Q. Regarding the system gain (K), it is concluded that the integration of the heat exchanger implies a great decrease in K (~ 61 %). This is also logical as the inlet wastewater is pre-heated, thus reducing its impact on the photoreactor stability. From a control perspective, this is an advantage, as the inlet water temperature (T_{in}) acts as a process disturbance (Fig. 3). Comparing both system models (electrovalve and photoreactor) it is concluded that the secondary loop (electrovalve) is 72 times faster than the primary loop (photoreactor). This a critical condition that justify the cascade control strategy (Åström, 2006). Primary control loop was tuned considering the dynamic response of the plant when setting to manual and automatic mode the primary and secondary loop, respectively (Table 3). Note that in this case step changes to secondary control setpoint (Q_{sp}) were performed.

Table 2. Characteristic first-order parameters for the linear model of the Fresnel solar collector.

Q vs T_{out} (Input vs Output)	First-order model parameters		
Plant configuration	Gain (K) [°C / (L/h)]	Time constant (τ) (sec)	Time delay (Θ) (sec)
No heat recovery	-0.157	163	67
Fresnel + heat exchanger	-0.061	138	66

Table 3. Characteristic first-order parameters used to tune primary control loop (Fresnel solar collector).

Q_{sp} vs T_{out} (Input vs Output)	First-order model parameters		
Plant configuration	Gain (K) [°C / (L/h)]	Time constant (τ) (sec)	Time delay (Θ) (sec)
No heat recovery	-0.157	171.1	73.9
Fresnel + heat exchanger	-0.061	145.1	70.4

5.2 Control system test

Primary and secondary PI controllers were tuned using Lambda method as discussed above, based on the empirical modelling study of the plant (Table 1 and Table 3). Closed-loop tuning parameters can be found in Table 4 for the different configurations of the plant. Primary loop PI controller was tuned considering a closed-loop time constant value equal to the open-loop system constant time ($\lambda = \Theta$). Nevertheless, secondary control loop tuning was conducted assuming $\lambda = 2.4\ \Theta$. These values were selected looking for a smooth Q variation to reduce T_{out} overshooting, based on typical values used in process control (Skogestad, 2003).

Table 4. Cascade control system tuning parameters for the different plant configurations.

Closed-loop tuning parameters	Secondary PI controller *	Primary PI controller **	
		No heat recovery	Fresnel + heat exchanger
λ	5.5 sec	73.9 sec	70.4 sec
K_p	$+3.62 \cdot 10^{-4}\ \frac{\text{Volt}}{\text{L/h}}$	$-7.36\ \frac{\text{L/h}}{°\text{C}}$	$-16.80\ \frac{\text{L/h}}{°\text{C}}$
T_i	2.3 sec	171.1 sec	145.1 sec
T_t	1.51	13.08	12.05

* Q_{sp} vs Voltage ** $T_{out,sp}$ vs Q_{sp} (Setpoint vs Control Action)

The cascade control approach was tested in the prototype plant by setting different operating temperature setpoints (Fig. 4 and Fig. 5.a). Step changes of ± 10 and ± 20 °C were conducted in the range of 40-70 °C. First, a batch start-up of the plant was programmed when switching on the cascade control system. Once the initial pre-set operating temperature was achieved (50 °C) the control system was set to automatic mode. Then, wastewater feed flow (Q) was automatically modified by the control system to achieve target operating temperature in each case (primary control setpoint).

The implementation of a heat exchanger enhanced the plant stability by reducing T_{out} overshooting. This is logical, as inlet water temperature (T_{in}) is higher due to previous pre-heating (Fig. 5.b). Note that T_{in} is a disturbance (Fig. 3) which significantly affects target process variable (T_{out}). Its variability is limited by the room temperature when the plant is operated with no heat recovery stage (Fig. 4). Nevertheless, when a pre-heating stage is implemented in the plant, T_{in} strongly depends on T_{out}. Increases in T_{in} up to 15 °C were achieved respect to the temperature of the water in the storage tank (T_{tank}), depending on the operating conditions (Fig. 5.b). Note that when the plant is operated without a pre-heating stage $T_{in} = T_{tank}$ (Fig. 2).

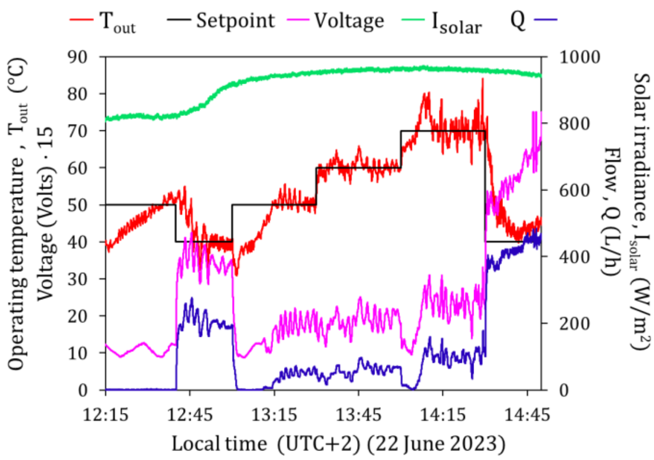

Fig. 4. Cascade control system test (no heat recovery operation) ($T_{in} = 29.2 \pm 0.7$ °C).

The cascade control approach also allows the operation of the plant in manual mode by switching off the primary control loop. Therefore, the operator is able to set a constant operating wastewater feed flow (secondary control setpoint, Q_{sp}) and the secondary PI controller automatically modifies electrovalve voltage to achieve it. It is worth highlighting the need to provide a PI control on the proportional electrovalve (Voltage vs Q), as the water height in the 5-m^3 raw secondary effluent storage tank may affect pumped wastewater feed flow (Q).

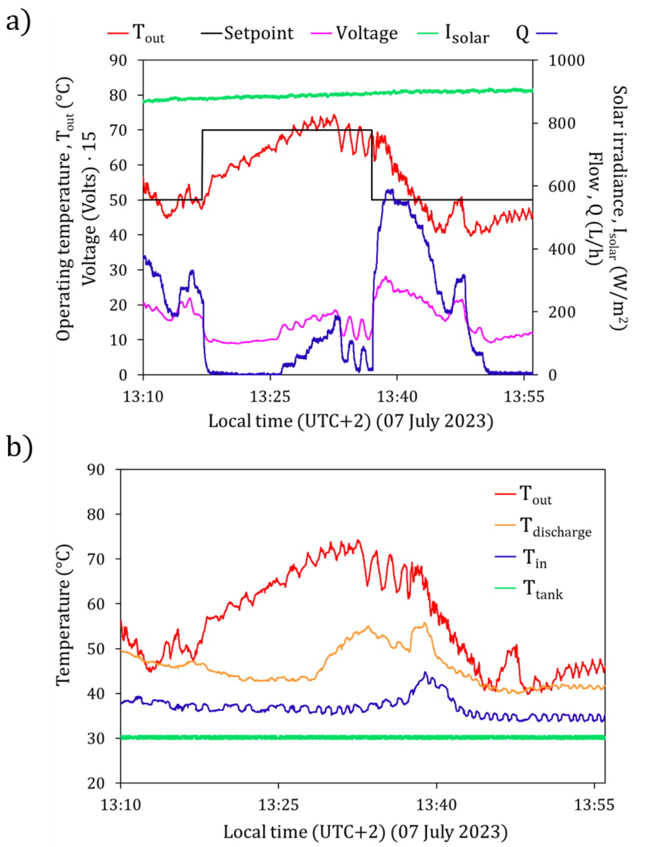

Fig. 5. Cascade control system test (Fresnel + heat exchanger). Solar collector operation (a) and heat exchanger monitoring (b).

Note that results shown in Fig. 4 and 5 present a noisy behaviour, and the use of noise filters will be considered in future experiments.

5.3 Continuous flow operation at demonstration scale

An automatic operation of the plant was conducted to evaluate *Escherichia coli* (*E. coli*) and total coliforms (TC) disinfection efficiency in continuous flow mode (Section 5.3.1 and Section 5.3.2). To this end, Log Reduction Values (LRV) were computed based on microorganism concentration. The detection limit (DL) was one colony-forming unit (CFU) per 100 mL (1.E+0 CFU/100 mL).

5.3.1 Operation at design basis (no heat recovery)

E. coli and TC inactivation were evaluated at design basis (no heat recovery) for the continuous flow operation of the plant at different operating temperatures (Fig. 6). Results show that operating temperatures above 60 °C are required to achieve significant *E. coli* and TC inactivation. LRV for *E. coli* inactivation of 2.85 and 4.78 were achieved at 60 and 70 °C, respectively. Note that final *E. coli* concentration at 60 °C ($1.4 \cdot 10^3$ CFU/100 mL) and 70 °C ($1.63 \cdot 10^1$ CFU/100 mL) correspond to water qualities Class D ($\leq 10^4$ CFU/100 mL) and Class B ($\leq 10^2$ CFU/100 mL), respectively, according to EU 2020/741 Regulation. Regarding water treatment capacity (Table 5), it was higher for a 70-°C operating temperature (100 L/h) compared to 50 °C (50 L/h), even though similar solar irradiances were measured (~ 950 W/m^2). It is concluded that not only the operating temperature and the solar irradiance availability, but also the local time, affects the treatment capacity of the plant. This is logical as a north-south orientation of the solar collector was adopted to maximize solar concentration at solar noon (Berrada et *al*., 2021). Note that the 50-°C and 70-°C operating temperatures were evaluated at 13:30 and 14:30 (hh:mm UTC+2, 22 June 2023), respectively.

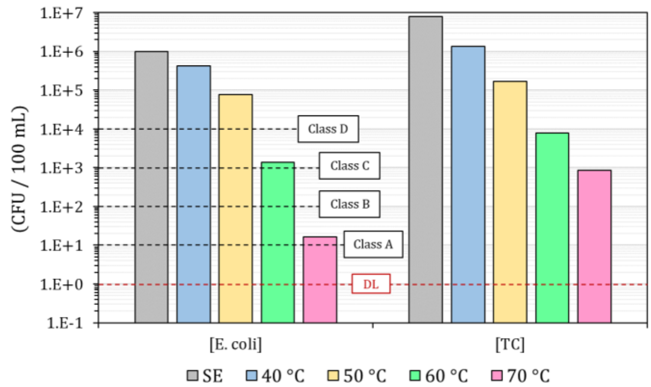

Fig. 6. Effect of T_{out} in *E. coli* and TC inactivation for a design basis operation of the plant (no heat recovery) in continuous flow and automatic mode. SE and DL stands for WWTP secondary effluent and detection limit, respectively. Water quality classes (A, B, C and D) according to EU 2020/741 Regulation are represented using black dashed lines.

Table 5. Operation at design basis (no heat recovery) in continuous flow and automatic mode. Date of experiment: 22 June 2023 (T_{in} = 29.2 ± 0.7 °C).

T_{out} (°C)	Local time * (UTC+2)	Q (L/h)	HRT (min)	LRV		Water Quality Class
				E. coli	TC	
40	13:00	200	5.2	0.37	0.77	-
50	13:30	50	20.8	1.10	1.68	-
60	14:00	65	16.0	2.85	3.00	D
70	14:30	100	10.4	4.78	3.97	B

* Solar irradiance profile is shown in Fig. 4.

5.3.2 Upgraded operation (heat exchanger)

The upgraded design of the plant (energy recovery stage) was also evaluated for a continuous and automatic operation of the process (Fig. 7). LRV for *E. coli* of 0.30, 1.96, 5.57, and 5.57

were obtained when T_{out} was set to 40, 50, 60, and 70 °C, respectively. LRV achieved correspond to water qualities Class D (50 °C, 200 L/h) and Class A (60 and 70 °C, 150 and 100 L/h, respectively). Note that higher reclaimed water qualities were attained when compared to the no heat recovery operation (Fig. 6). Additionally, water treatment capacity (Table 6) was significantly increased (up to 400 %, depending on the operating conditions) even though average solar irradiance was slightly lower for the upgraded design operation of the plant compared to the no heat recovery operation (877 vs 940 W/m^2). Results show that pre-heating stage not only increases water treatment capacity but also promotes *E. coli* disinfection enhancement. This may be explained by the fact that pre-heating stage implementation leads to longer exposure times of bacteria to temperature, even though hydraulic residence times (HRT) are reduced. Note, for instance, that Class D is achieved when operating the plant at 50 °C (Fresnel + heat exchanger) and 60 °C (no heat recovery), being the treatment capacity ~ 3 times higher for the upgraded design (200 vs 65 L/h, respectively). This operating approach is not common when using Fresnel solar concentration technology, as steam generation or pre-heating is usually the target when applied in industrial processes (Pitz-Paal, 2020). However, the demonstration plant is oriented towards wastewater reclamation (bacteria disinfection) and not thermal energy generation. Hence, the plant design and the operating strategy are addressed from different perspectives even though the same technology is used.

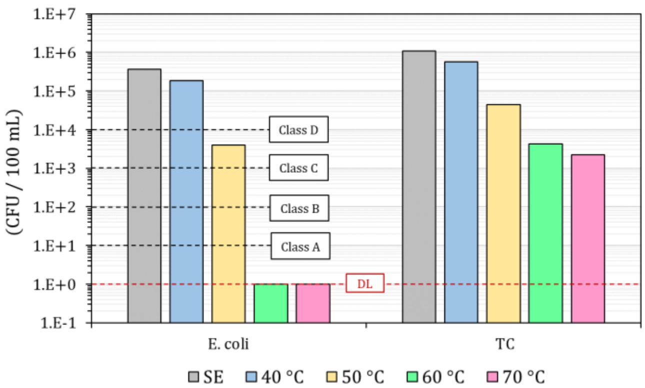

Fig. 7. Effect of T_{out} in *E. coli* and TC inactivation for the upgraded design of the plant (Fresnel + heat exchanger).

Table 6. Upgraded operation in continuous flow and automatic mode (Fresnel + heat exchanger). Date of experiment: 25 and 26 July 2023 (I_{solar} = 877 ± 13 W/m^2).

T_{out} (°C)	T_{in} (°C)	$T_{discharge}$ (°C)	Q (L/h)	HRT (min)	LRV *E. coli*	LRV TC	Water Quality Class
40	33	36	740	1.4	0.30	0.28	-
50	36	46	200	5.2	1.96	1.38	D
60	38	43	150	6.9	5.57	2.39	A
70	45	54	100	10.4	5.57	2.67	A

6. CONCLUSIONS

Results proves not only the feasibility of using Fresnel-type solar concentration technology for urban wastewater reclamation purposes, but also show the great impact of implementing a thermal energy recovery stage in the process, simultaneously enhancing water treatment capacity and bacteria disinfection. The proposed control algorithm allows to adequately regulate the Fresnel solar system temperature, thus contributing to achieve a stable operation of the plant.

Future works will explore the use of gain scheduling approaches to account with the non-linearities of the system, and the application of feedforward compensators to compensate for measurable disturbances.

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