Analyse expérimentale et numérique de l’encrassement de récupérateurs de chaleur sur eaux grises de douche

Experimental and numerical analysis of shower drain water recovery heat exchangers fouling.

Jean-Baptiste BOUVENOT[1,2*]
1: ICube laboratory, University of Strasbourg, France
2: INSA Strasbourg, 24 Boulevard de la Victoire, 67000 STRASBOURG
*(auteur correspondant : jean-baptiste.bouvenot@insa-strasbourg.fr)

Résumé - La récupération de chaleur sur eaux grises est une stratégie intéressante qui peut réduire considérablement la consommation d'énergie des bâtiments pour l'eau chaude sanitaire. Cependant, ces échangeurs contiennent du côté chaud de l'eau contaminée (graisses, matières organiques) et en contact avec de l'oxygène, ce qui favorise le développement d'un biofilm. Ce biofilm a un impact potentiellement important sur les performances de ces échangeurs. L'objectif de cette étude est d'analyser les données expérimentales d'une année et d’en déduire un modèle analytique basé sur des données simulant le développement du biofilm et la résistance de contact pour l'utiliser dans les codes de calcul.

Abstract - Heat recovery from grey water is an interesting strategy that can drastically reduce buildings energy consumption for domestic hot water. However, these exchangers contain warm water on the hot side that is contaminated (grease, organic matter) and in contact with oxygen, which encourages the development of biofilm. This biofilm has a potentially significant impact on the performance of these exchangers. The aim of this study is to analyze one year's experimental data and to derive an analytical data driven model simulating biofilm development and contact resistance for use in calculation codes.

Nomenclature

COP	coefficient of performance
E	heat exchanger efficiency, -
k_f	fouling coefficient, kJ.K^{-1}.m^{-2}.d^{-2}
NTU	number of transfer units, -
q_v	volume flow rate, m^3.h^{-1}
R_f	fouling thermal resistance, m².K.kW^{-1}
$R_{f\infty}$	asymptotic thermal resistance, m².K.kW^{-1}
US	thermal conductance, W.K^{-1}
T	temperature, K
T	duration, day or weeks

Index and exponent

0	nominal/initial
cwi	inlet cooling water (from the network)
cwo	outlet cooling water (after the HX)
f	fouling
gr	growth
hx	heat exchanger
ind	induction
mix	mixing temperature

1. Introduction

Domestic hot water (DHW) is a major source of energy consumption in residential buildings (second behind heating), accounting for 16% in France [1, 2] in 2021 (15% in Europe in 2021 [3], 18% in the United States in 2023 [4]). This rate has risen steadily, doubling over the last 50 years in France [1,2], due to improvements in the thermal performance of buildings (increasingly stringent regulations (RT 2012 and RE2020)) and higher levels of comfort, particularly with more frequent showers. This rate will be even higher for high-performance buildings (new or renovated), reaching around 30% [5]. The energy consumed for DHW dedicated to showers in France will represent around 49 TWh in 2021 [1], of which 24 TWh [1] will be produced using electrical energy, mainly Joule-effect systems (around 11 million units) which operate mainly at night during off-peak hours. This basic electricity consumption

https://doi.org/10.25855/SFT2025-012

is mainly covered by nuclear power plants. This represents the electricity production of around 2 nuclear reactors (out of 57 in France in 2024). Among DHW consumption, shower consumption accounts for around 2/3 of the total. It also happens to be the easiest source of heat to recover (‘lightly charged’ grey water compared with ‘heavily charged’ grey water, i.e. oily water). In addition to the gains in terms of energy efficiency and GHG emissions, recovering some of this energy offers the opportunity to free up electrical capacity in view of the growing use of electric mobility, which will require large quantities of energy during this same night-time period to recharge. Often, we work to improve DHW production (thermodynamic hot water heaters TWH, heat pumps, solar thermal panels, biomass, etc.) without bothering to recover the heat lost during the evacuation of grey water that is still hot. However, this is what is commonly done in a double flow ventilation system, for example. Furthermore, in energy terms, only 20% of the total heat produced is used (heat that is used/lost by convection with the skin and by evaporation between the shower head and the drain (see Fig.1)). 80% of the heat produced will be evacuated through the drain (powers of the order of 10 kW):

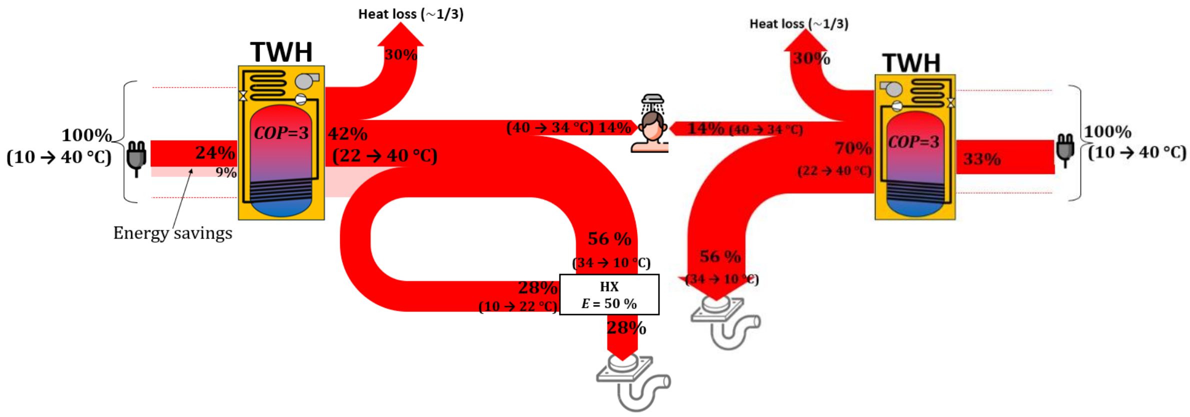

Figure 1 : *Sankey diagram comparing TWH with and without drain water heat recovery*

Figure 1 shows an example of an energy balance for the production of DHW by a TWH with and without a heat recovery unit. The gain from a standard heat recovery unit (E_{hx}=50%) can be estimated at around 30%. It can also be seen that static losses become the majority in this case. It is relatively easy to recover this heat, either via passive, gravity heat exchangers, or via active thermodynamic systems that use this waste heat as a heat sink. The latter are obviously relevant, but the advantages of the first solution are its low technology, low maintenance (no moving parts), long life and low cost. The major disadvantage, however, lies in its integration, since it requires a gravity heat exchanger that should ideally be located below and as close as possible to the grey water drain, which is not always possible (single-storey houses or flats). TWH are also being used more and more to replace traditional Joule-effect electric water heaters (EWH), making it possible to improve the energy efficiency of DHW production in buildings by a factor of around 3 (corresponding to the coefficient of performance *COP*). This system is obviously relevant in the current context (energy/climate issues), however, these systems are particularly sensitive to fouling due to the nature of the primary fluid: charged grey water (slightly oily water) containing organic matter and the presence of oxygen (free surface flow in uncharged pipes). In particular, biofilm growth can be observed in these pipes, preventing heat transfer and obstructing the flow. Previous studies have analyzed the parameters influencing energy performance (flow rate, hydraulic connections) [6-7] or the impact of these heat recovery units on the performance of thermodynamic water heaters [8]. The first aim of this study is to analyze experimentally the dynamics of fouling and biofilm development on the basis of in situ tests carried out over a long period (14 months) and with a high sampling rate (6s time step). This study then proposes an analytical model with parameters identification based on calibration of the model with the experimental data.

2. In situ test

A heat recovery unit has been installed in a flat for a family of 3 people (2 adults and a small child (<1m)) in an urban context (Strasbourg, France). The technical installation consisted of DHW production using a 200 l electric water heater tank (Joule effect), and an Ehtech Obox heat recovery unit (see Fig. 2) connected to both the DHW tank and the thermostatic mixing valve installed directly under the shower tray. The distance between the drain and the recovery unit is very small (30 cm) and has been thermally insulated. A thermostatic mixer adjusts the temperature according to the set point (around 40°C in practice) and according to the temperature at the outlet of the heat recovery unit. In terms of metrology, we used type K thermocouples to measure the temperatures of cold water T_{cwi}, preheated water T_{cwo}, water drawn off at the shower head T_{mix} and water at the drain T_{drain} (see Fig.2). A data logger with a 6 s time step was used. These thermocouples have been tested beforehand in a controlled water bath to be calibrated.

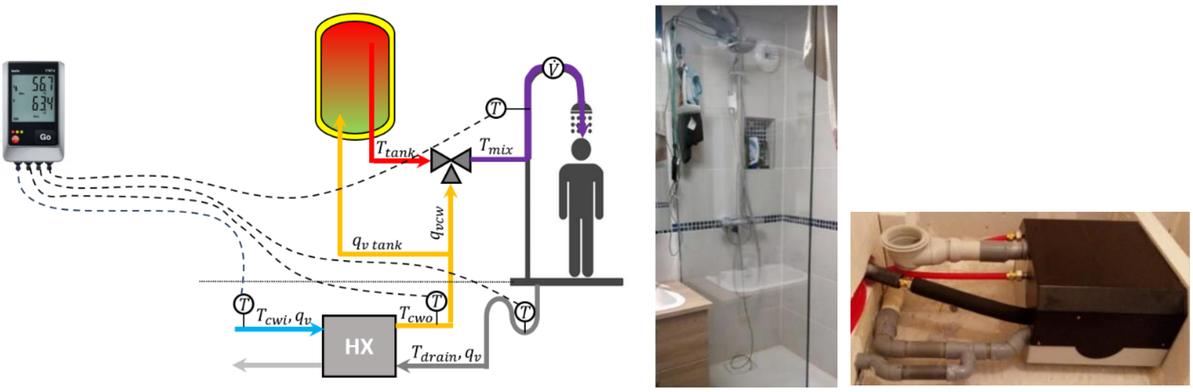

Figure 2: *Sensor location and photo of the tested device*

Physical quantity	Technology	Accuracy	reference
temperature	Armoured Type K Thermocouple	∓0,6 K	Data logger Testo 176 T4
Water volume	Blades sensor	∓8 %	Amphiro b1connect

Table 2 : *Sensors characteristics*

The results of the *in situ* test highlighted the significant impact of heat exchanger fouling. Figure 3 shows the impact of the flow rate, but also the difference between nominal operation and operation degraded by fouling. In particular, an average efficiency of 66% is measured, compared with a nominal efficiency of 72%, i.e. a drop of 8% (or 6 points). We also plot on Fig.3 a theoretical curve of theoretical HX efficiency by applying the *NTU* theory and by taking into account the impact of mass flow variation on thermal conductance of the heat exchanger *US* from previous works [7].

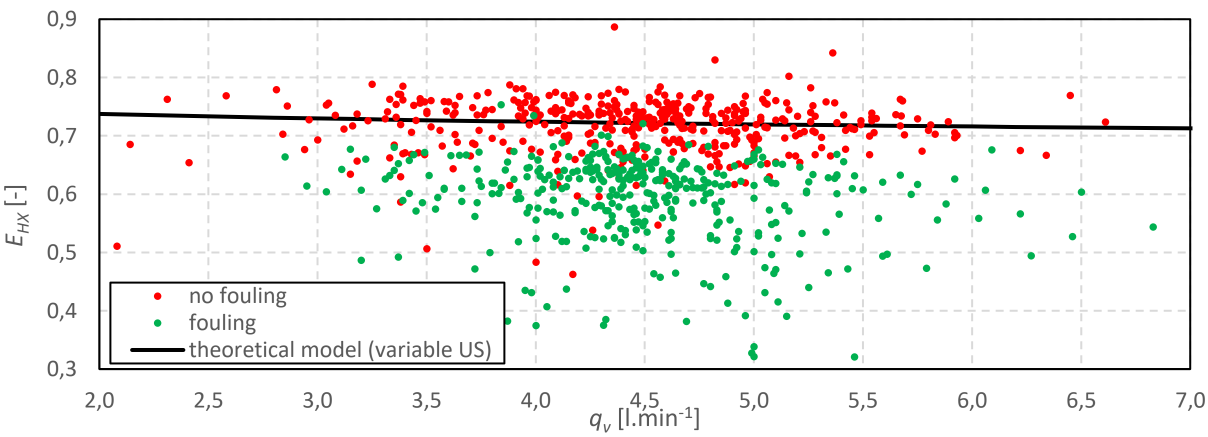

Figure 3: *Average exchanger efficiency per shower as a function of DHW shower flow rate*

3. Fouling model

As can be seen in Figure 4, there is a particular fouling dynamic characterized by an S-shaped curve characteristic of biofilm development, with an induction phase, followed by a growth phase and then a stabilization phase which is not reached here.

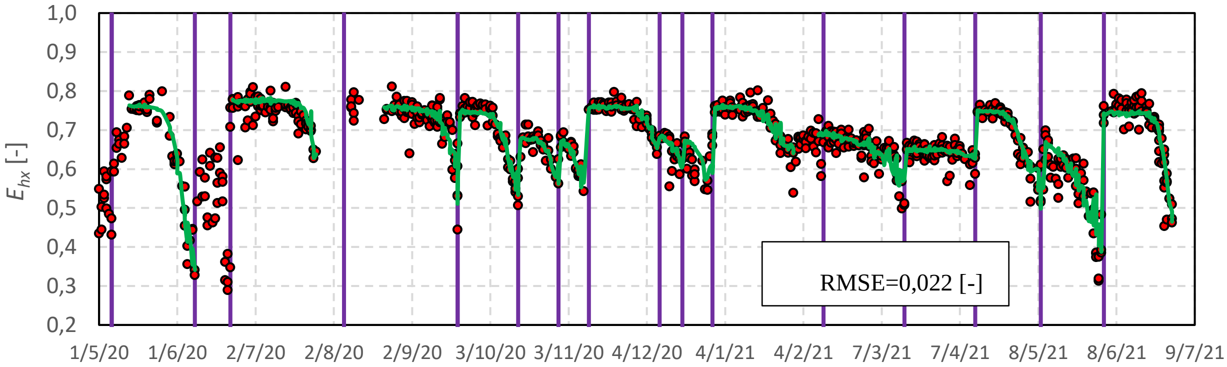

Figure 4: *Evolution of HX efficiency over the time (measurements in red and model in green), chemical purge planning and fouling modeling*

The *in situ* study showed a significant impact linked to fouling on the "grey water" side due to the various elements contained in the grey water (soap, epidermis, body fluids) as well as the presence of oxygen due to a pipe that is not under load. The dynamics observed correspond to the development of a biofilm feeding on this organic matter in an aquatic environment and in the presence of oxygen. Various models exist for modelling the thermal resistance of fouling in relation to this biofilm development. Various authors have already worked on the fouling of heat exchangers, mainly for fouling problems in hot water circuits (DHW or heating) [9] or for seawater exchangers [10] or cooling circuits [11]. Others have also studied these fouling resistances on heat exchangers using sewage water [12-13]. Very few studies have focused specifically on fouling in grey water heat exchangers and, more specifically, on fouling in shower water heat exchangers. Only Grundén et al [14] have set up an experimental protocol to attempt to assess this, but with poor results. Shen et al [15-17] worked on a heat pump assisted by shower drain water and were able to characterize the fouling dynamics in relation to the development of a biofilm. Various models exist to simulate the development of a biofilm on the exchange surface of a heat exchanger. There are the historical models of Kern (exponential) [18] and of Konak, which introduces asymptotic fouling based on the concept of a driving force for the development of deposits [19]. Finally, more recently, Nebot [20] has proposed an adaptation of Konak's model to reproduce "S-curve" dynamics with an induction phase T_{ind}, an exponential growth phase T_{gr} and a stabilization phase (see Fig. 5) with a fouling thermal resistance that stabilizes at $R_{f\infty}$ (see Eq. 1 and Eq.2). This model has been used by many authors mainly to study the best way to clean the heat exchangers.

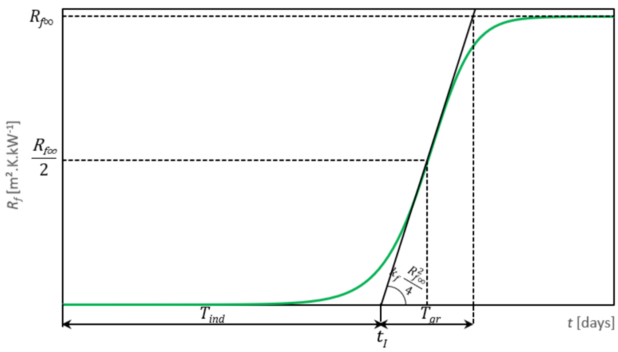

Figure 5: *Nebot biofilm modeling approach*

We define the fouling thermal resistance R_f such as:

$$R_f = \frac{1}{US_f} - \frac{1}{US_0} \quad [20] \text{with } US_0 = \rho c q_v \frac{E_{HX\_0}}{1 - E_{HX\_0}} = 1365 \text{ W.K}^{-1} \tag{1}$$

$$\text{With } \begin{cases} \frac{dR_f}{dt} = k_f (R_{f\infty} - R_f) R_f \\ R_f(0) = R_{f0} \neq 0 \end{cases} [20] \tag{2}$$

We also define the way to compute the HX efficiency taking into account fouling:

$$NTU = \frac{US_f}{\rho c_p q_v} \quad \text{with } q_v = 8 \text{ l.min}^{-1} \tag{3}$$

$$E_{HX} = \frac{NTU}{1 + NTU} \tag{4}$$

4. Results

By applying the Nebot model [20] to the *in situ* test data set, the fouling cycles via biofilm development are fairly accurately reproduced. Chemical purges (soda) are indicated, and the induction and growth phases are clearly shown each time. An optimization procedure aimed at minimizing the error (Root Mean Square Error RMSE) between experimental results and the model's average efficiency per shower was carried out, yielding cycle-specific parameters rather than average parameters for the whole period (see table 2). The model parameters vary quite sensitively between each cycle. However, it is likely that the temperature of the mains water plays an important role in biofilm development, either as a catalyst or as a reaction inhibitor. This assumption seems to be confirmed by the data analysis, which shows faster fouling on average during hot periods (cold water at 20°C vs. 10°C in winter). Lastly, cleaning efficiency should vary according to the cycle, depending on the amount of residual organic matter remaining. This residual quantity is likely to influence the rate of biological development of the biofilm mainly for the induction phase, which would explain the disparity in results.

		R_{f0} (see eq. 2)	$R_{f\infty}$ (see eq. 2)	k_f (see eq. 2)	*RMSE*	T_{cwi}
Cycle number (see Fig. 4)	1	0,002	5,47	0,082	0,022	16
	2	1,03E-06	8,17	0,067		19
	3	0,00044	12,41	0,026		19
	4	0,00023	1,56	0,36		17
	5	0,00082	0,77	0,96		15
	6	0,046	1,19	0,47		14
	7	3,90E-05	1,13	0,42		13
	8	0,03402	2,16	0,18		12
	9	0,00254	0,65	2,43		12
	10	0,00069	0,84	0,41		11
	11	0,0312	2,99	0,04		11
	12	0,00098	0,48	0,48		12
	13	0,00108	1,46	0,32		13
	14	0,11299	7,36	0,02		15
	15	4,80E-06	2,98	0,24		17
	Mean	0,0073	1,1	0,19	0,067	15
		$m^2.K.kW^{-1}$	$m^2.K.kW^{-1}$	$kW.m^{-2}.K^{-1}.day^{-1}$	-	°C

Table 2: *Nebot model parameters for fouling cycles*

5. Study of the impact of purge frequencies

We now use the Nebot model and average parameters to study the influence of cleaning/purging frequency on the average efficiency of the grey water recovery heat exchanger. It is assumed that purging will return the heat exchanger to similar nominal conditions. Purging can be chemical, thermal, hydro-mechanical or a combination of these strategies. Different purge frequencies are assumed: annual (1), half-yearly (2), quarterly (4), monthly (12), fortnightly (24) or weekly (52). For each case, we plot the evolution of the fouling thermal resistance R_f and the heat exchanger efficiency E_{hx} (see figure 6) according to Eq. 1 to 4.

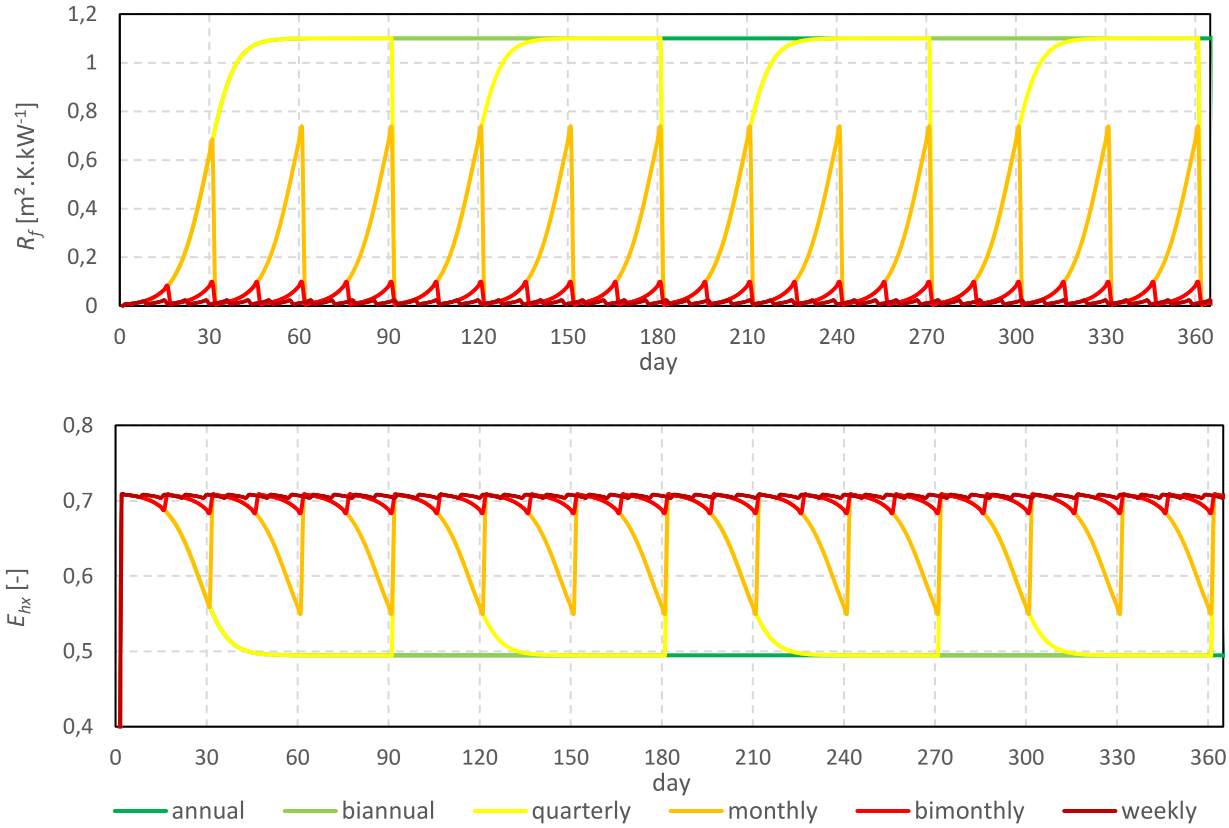

Figure 6: *Fouling thermal resistance and HX efficiency evolution according to purge frequency*

The influence of this parameter on performance can be seen in figure 7, which shows that, under the conditions studied, purging must be carried out at least once a month to limit the drop in efficiency due to biofilm development. Without purging, the efficiency of the heat exchanger can fall by up to 30% compared with nominal conditions. This result is close to the experimental results of Shen et al. on a coil type heat exchanger [15-17]. Exchanger efficiency remains correct, but reduced performance will reduce the economic, energy and environmental relevance of such systems. However, the same energy, economic and environmental costs will have to be evolved for the purging strategies employed (additional water consumed in the case of hydro-mechanical purging, energy to achieve thermal shock or use of expensive chemicals potentially harmful for the environment).

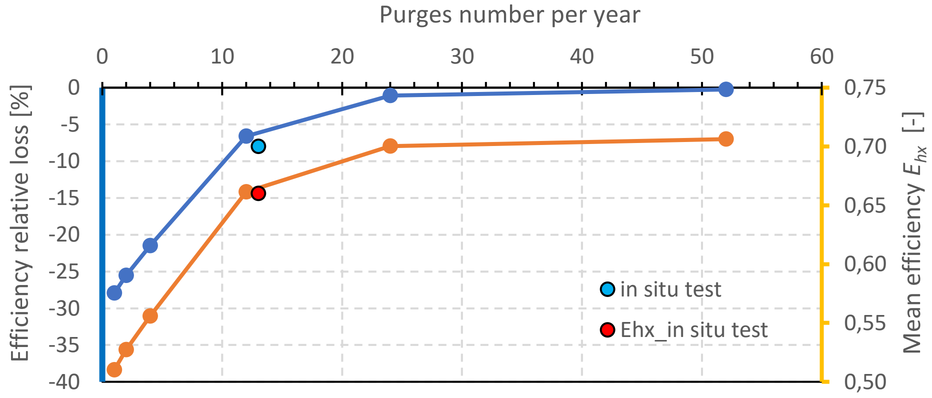

Figure 7: *Impact of purging rate on mean HX efficiency and efficiency relative loss*

6. Conclusion

Heat recovery from grey water therefore appears to be a promising lever for further reducing the energy consumption of buildings and freeing up electricity production capacity, particularly for electric mobility, as DHW production is already highly electrified. Combining a thermodynamic water heater with a heat recovery unit could potentially reduce DHW consumption by a factor of 4 to 6. However, the nature of the hot source is subject to significant fouling through the development of biofilm, which resists heat transfer. We have shown here that biofilm obeys a non-linear law (S-curve) with an induction phase lasting a few days to a few weeks and a growth phase lasting a few weeks. The stabilization phase is only reached after several weeks or even months. This fouling reduced the nominal efficiency of the exchanger from around 8% in the *in situ* test to a value of 66% with monthly chemical purges (see Figure 8). A theoretical study then showed the impact of purge frequency on the performance of these recovery systems. This study showed that without a purging strategy, with this type of plates heat exchanger, thermal performance could be reduced by a factor of 2. However, effective purging must be carried out at least once a month to limit the drop in efficiency to less than 10%. The energy, environmental and economic costs and effectiveness of the various purging strategies (thermal, mechanical, hydro-mechanical, chemical or combinations of these strategies) still need to be assessed.

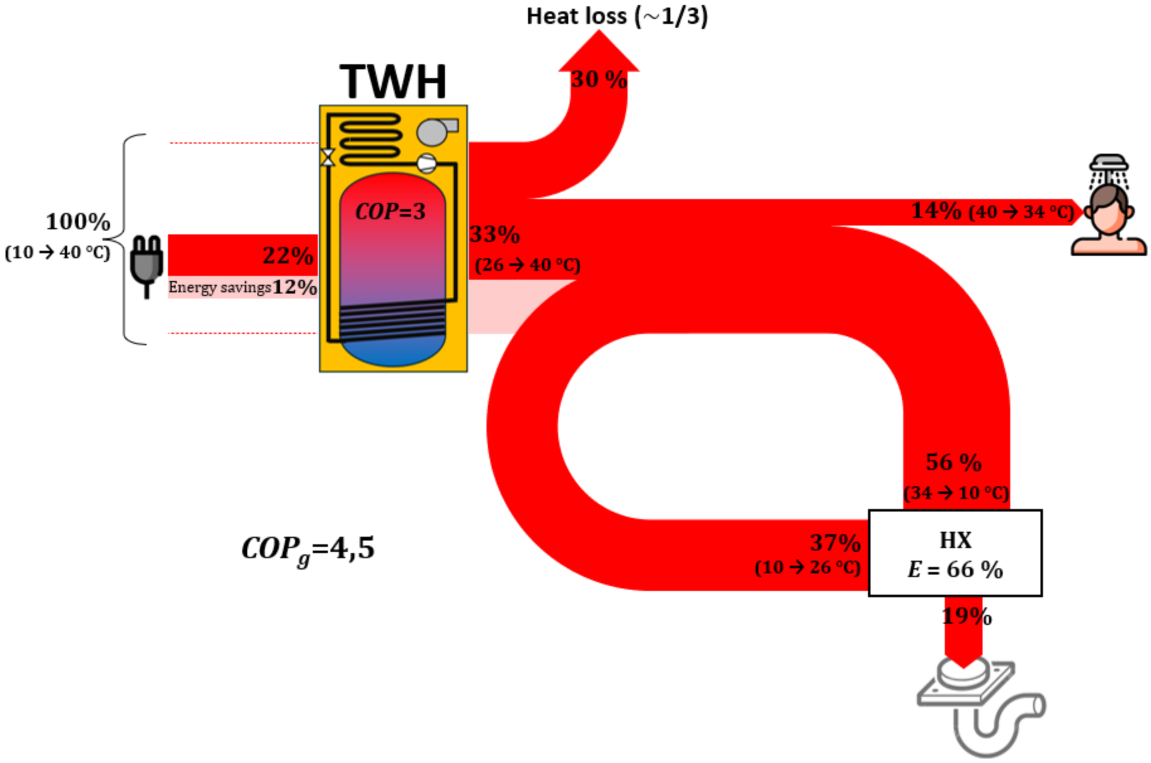

Figure 8: *Sankey diagram on TWH coupled to drain water heat recovery with in situ test results*

Finally, the energy balance presented in figure 8 shows the preponderance that static losses would have in this configuration (whether we have a thermodynamic or Joule-effect electric water heater): losses that will then have to be dealt with either by improving the thermal insulation of the tank or by using an instantaneous production system (Joule effect, gas or heat pump). If we over insulate the tank, it's possible to reach a global COP of 6 for DHW production in buildings.

References

[1] « 2018-climat-air-energie_chiffres-cles-010354.pdf ». Consulté le 7 février 2023
https://librairie.ademe.fr/cadic/1731/2018-climat-air-energie_chiffres-cles-010354.pdf

[2] « Énergie dans les bâtiments », Ministères Écologie Énergie Territoires ». Consulté le 3 avril 2023 https://www.ecologie.gouv.fr/energie-dans-batiments

[3] Deutz, K. R. (2018). *Optimisation du cycle de fonctionnement d'un chauffe-eau thermodynamique résidentiel* (Doctoral dissertation, Université de Lyon).

[4] https://www.energy.gov/energysaver/water-heating

[5] Enertech, *Etude sur la performance énergétique de copropriétés rénovées, Décembre 2023.* *https://www.enertech.fr/etude-sur-la-performance-energetique-de-coproprietes-renovees/*

[6] Bouvenot, J. B., Latour, B., & Arrayet, F. , Analyse théorique et expérimentale d'un système de récupération gravitaire de chaleur sur eaux grises. In *Congrès français de thermique*. (2020).

[7] Bouvenot, J. B., Beaudet C., In situ experimental and theoretical studies of the performance and the fouling impact of shower greywater heat recovery systems, *Energy and Buildings*, Vol. 331, (2025) https://doi.org/10.1016/j.enbuild.2025.115341.

[8] Bouvenot, J. B., & Beaudet, C. (2024). Etude d'un système de récupération de chaleur sur eaux grises couplé à un chauffe eau thermodynamique. In *Société Française de Thermique, Strasbourg, France, juin 2024.*

[9] Kapustenko, P., Klemeš, J.J., Arsenyeva, O. Plate heat exchangers fouling mitigation effects in heating of water solutions: A review. *Renewable and Sustainable Energy Reviews 179*, (2023)

[10] E. Eguía, A. Trueba, B. Río-Calonge, A. Girón, C. Bielva, Biofilm control in tubular heat exchangers refrigerated by seawater using flow inversion physical treatment, *International Biodeterioration & Biodegradation*, 79-87 (2008)

[11] Xu, Z., Wang, J., Jia, Y., *et al.* Experimental study on microbial fouling characteristics of the plate heat exchanger. *Applied Thermal Engineering*, (2016), vol. 108, p. 150-157.

[12] Chang, S., Chen, J., et Shi, L.. Using thermal shock to inhibit biofilm formation in the treated sewage source heat pump systems. *Applied Sciences*, (2017), vol. 7, no 4, p. 343.

[13] Chen, X., Yang, Q., Wu, R., *et al.* Experimental study of the growth characteristics of microbial fouling on sewage heat exchanger surface. *Applied Thermal Engineering*, (2018), p. 426-433.

[14] Grundén, E., & Grischek, M. (2016). Testing the Heat Transfer of a Drain Water Heat Recovery Heat Exchanger.

[15] C. Shen, Y. Jiang, Y. Yao, X. Wang, An experimental comparison of two heat exchangers used in wastewater source heat pump: A novel dry-expansion shell-and-tube evaporator versus a conventional immersed evaporator, *Energy*, Vol. 47, (2012), p 600-608

[16] Shen C., Jiang Y., Yao Y., Deng S., Experimental performance evaluation of a novel dry-expansion evaporator with defouling function in a wastewater source heat pump, *Applied Energy*, Vol. 95, (2012), p. 202-209

[17] C. Shen, L. Yang, X. Wang, Y. Jiang, Y. Yao, An experimental and numerical study of a de-fouling evaporator used in a wastewater source heat pump, *Applied Thermal Engineering*, Vol. 70, (2014), p. 501-509

[18] Kern, D. A theoretical analysis of thermal surface fouling. *Br. Chem. Eng.*, (1959), p. 258-262.

[19] Konak, A. R. Prediction of fouling curves in heat transfer equipment. *Trans. Inst. Chem. Eng*, (1973), vol. 51, p. 377.

[20] Nebot, E., Casanueva, J. F., Casanueva, T., *et al.* Model for fouling deposition on power plant steam condensers cooled with seawater: Effect of water velocity and tube material. *International Journal of Heat and Mass Transfer*, (2007), vol. 50, no 17-18, p. 3351-3358.