

Preliminary experimental studies on coalescer efficiency for liquid-liquid separation

I M Carraretto^{1,*}, D Scapinello¹, R Bellini¹, L P M Colombo¹, L Molinaroli¹ and G Manzolini¹

¹ Dipartimento di Energia, Politecnico di Milano, via Lambruschini 4a, 20156 Milano (MI), Italy

* Corresponding author: igormatteo.carraretto@polimi.it

Abstract. The international organizations have identified both water demand and accessibility as critical challenges with both current and future implications for human well-being. In reason of that due to the growing demand, it is essential to advance the technologies used in freshwater production, focusing on sustainability while maintaining operational efficiency. Within the HORIZON 2020 program, it was thought to integrate the desalination processes with Renewable Energy Sources (RES). The desalination process is based on Forward Osmosis (FO), which uses a membrane to split pure water from seawater by exploiting the osmotic pressure difference between the feed solution (i.e., seawater) and the draw solution (i.e., permeate side). For the process to be effective, a low-cost method for regenerating the diluted draw solution is necessary. Hence, a viable alternative is to deploy a thermo-responsive polymeric draw agent that can be regenerated by the heat power rejected from a CO₂ power cycle integrated with a Concentrated Solar Power. To perform the separation, a liquid-liquid separator (i.e., coalescer), mostly deployed in the oil and gas sector, is proposed to split the fresh-water from the polymeric draw solution. Hence, the aim of this work is to preliminarily assess the performances of the coalescer, aiming at the formulation of an experimental efficiency expression. Expression that is function of: (1) temperature at which the regeneration is performed, (2) residence time, and (3) draw concentration in the initial solution. The draw agent used in the experimental campaign is the PAGB2000, a thermo-responsive co-polymer that has a Lower Critical Solution Temperature (LCST) above which the fluid splits in two distinct phases: a polymer-rich (more concentrated), and a polymer-poor (more diluted). From the analysis it results that the coalescer performances strongly increase with both temperature and residence time, indeed efficiency achieves values near to 100%. On the other hand, the performances slightly worsen with increasing the initial draw concentration. Eventually, having an efficiency formulation can both help the design process of the desalination plant and provide an understanding on how much this technology can be applied in context far from the ones it was developed for.

1. Introduction

Water demand and accessibility have been recognized as two of the most critical tasks for human well-being in the near future [1]. Hence, because of the increasing need in fresh-water production through desalination processes, there is a strong interest in improving the technologies employed without neglecting both sustainability and efficiency.



Specifically, the desalination of seawater is a well-known technology to provide communities with freshwater where there is limited access to conventional resources. Historically, most desalination plants have relied on either Multi-Effect Distillation or Multi-Stage Flash technologies, often in conjunction with fossil fuel power stations [2]. Nowadays membrane based processes have gained space in the market [2]. The process can be made more environmentally sustainable by having a coupling with renewable energy sources. Perhaps, Reverse Osmosis membranes can be coupled with Photovoltaic systems [3] or, as in the case here proposed, Forward Osmosis membranes can be coupled with Concentrated Solar Power plants exploiting the waste heat that otherwise would be dissipated.

The FO process, similarly, to the RO process, is a membrane-based technology, however it deploys a different governing mechanism which is the osmotic pressure difference between the feed and the draw sides. It is indeed the above-mentioned pressure difference that promotes the flow of freshwater across the membrane. On the other hand, the solute or salt molecules present in the seawater are selectively prevented from passing [4]. The now-diluted draw requires additional treatment to split the fresh-water from the re-concentrated draw, enabling its future reuse. In particular, the regeneration process depends on the selected draw. Hence, to guarantee a low-cost regeneration a draw agent [5] that shows a thermo-physical response was selected, with the intention to regenerate it with the heat rejected from a power cycle as presented in Figure 1.

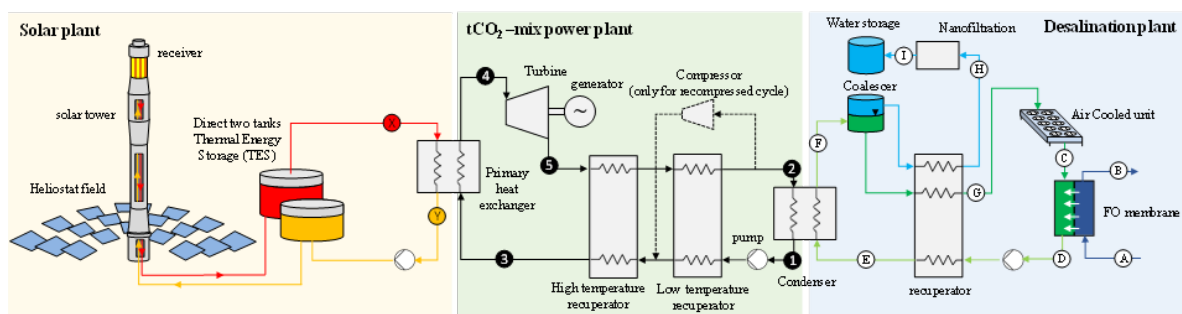


Figure 1. Layout of the integrated CSP+D system for a current central tower CSP plant.

This concept underpins the European Project DESOLINATION, which utilizes an advanced power cycle based on CO₂ blends to release heat at temperatures exceeding 75 °C, facilitating the regeneration step of the forward osmosis process [6].

Based on the analysis conducted by Inada et al. [7], [8], a LCST polymer can be the right draw agent, providing both high osmotic pressure and an easily-accomplishable regeneration process. However, the simplicity, feasibility, and effectiveness of the polymer regeneration process are critical factors that must be examined to ensure proper plant design. As noted by Colciaghi et al. [9], a coalescer is selected to perform the regeneration step.

The coalescer is a static separator, mainly used in the petrochemical sector, able to split two distinct immiscible liquids from a stable emulsion (liquid-liquid) or purifying a gas from impurities to achieve high-quality gas (gas-liquid).

The idea of employing a coalescer gravity separator was for the first time presented by TREVI System and then subsequently investigated by Ahmed et al. [10]. Their work evaluates the technical feasibility of using a thermo-responsive polyelectrolyte draw solution in a forward osmosis desalination pilot-scale system with a capacity of 10 m³/day. In particular, they consider both DS and feed flowrates effect on the net water recovery and product water flowrates of the system. The selected draw solution demonstrated its potential for use in commercial-scale forward osmosis desalination plants due to its low viscosity and ease of phase separation, utilizing a coalescer regeneration system operating at a temperature of 85 °C.

Given the limited studies available in the open literature on both experimental and modeling results, a preliminary experimental campaign was conducted to evaluate the performance of the

coalescer in regenerating a thermo-responsive draw agent at varying temperatures, flow rates, and initial solution concentrations. The aim was to gather data to develop an empirical expression for its efficiency.

2. Materials and Methods

2.1. Description of the test facility

The experimental setup (Figure 2) is created to reproduce the regeneration step of the diluted draw agent deployed in the FO plant (Figure 1 blue box), considering a draw agent composition as it is at the outlet of the FO membrane.

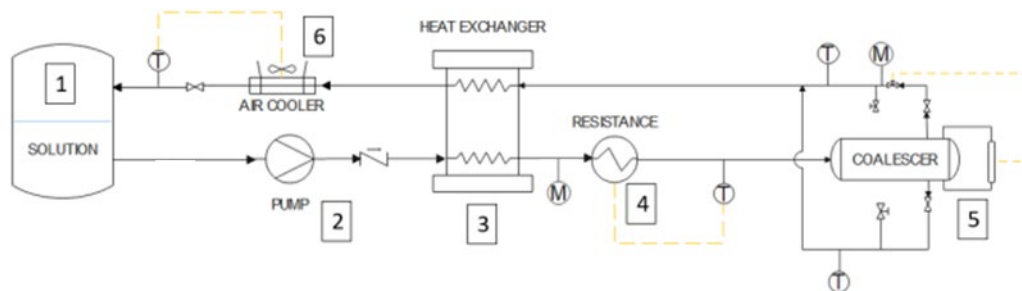


Figure 2. Experimental facility layout.

A tank (1), positioned 1 meter above the centrifugal pump (2) to avoid cavitation during operation, holds the draw solution at atmospheric pressure and at a temperature lower than the LCST. A centrifugal pump is used to set the fluid flowrate and to force it to pass via first the pre-heating section (3) and then via the heating one (4). Electric resistances are adopted to heat the draw solution from the inlet temperature up to the regeneration one (T_{reg}). The fluid then flows into the coalescer (5), where the split between the two phases, poor and rich respectively, occurs. A metal mesh is inserted within the coalescer to facilitate the coalescing process. The flow is subsequently divided into two streams: (i) the polymer-rich phase, which exits the coalescer from the bottom, and (ii) the water-rich phase, which exits from the top. Each section has its own tap for sampling. The two streams are subsequently recombined and directed into the hot side of the heat exchanger (3). Finally, at the heat exchanger outlet, the fluid is cooled by an air cooler (6) before returning to the storage tank (1).

Within the coalescer ($D = 0.20$ m, $L = 1.60$ m) a metal mesh (STYLE42C, Costacurta S.p.A.-VICO, Milano, Italy) is tested, the mesh density (ρ_M) is of 262 kg/m³.

The selected polymer is PAGB2000 whose thermo-physical properties are presented in [11]. The polymer has already been recognized in studies published in the open literature as a promising option in Forward Osmosis processes [9]. The product is available on the market with the commercial name of UNILUBE 50MB-26, and it is produced by NOF Corporation® (Tokyo, Japan) and deployed without further purification.

2.2. Measurement and instrumentation

In the experimental setup, four thermo-resistances (RTD Pt100 IEC751 cl.A, Smeri, Assago (MI), Italy) are adopted to measure the temperatures and are positioned at: (1) the inlet of the coalescer measuring T_{reg} , (2) the outlet of the coalescer on both branches measuring either T_{rich} or T_{poor} , (3) the outlet of the air cooler measuring T_{cooler} . Two flow-meters are used to measure the volumetric flowrate and are placed at: (1) the outlet of the heat exchanger measuring the total flowrate (F) (PromagP300, 0 - 100 l/min, $\pm 0.5\%$ r.v., Endress Hauser, Reinach, Switzerland), (2) at the outlet of polymer-poor (water-rich) branch (HTLD-MAG, 0 - 100 l/min, $\pm 0.5\%$ f.s., Smeri, Assago (MI), Italy) measuring the

water produced (F_{poor}). The concentration of the polymer solution is measured using a portable refractometer (MA871, 0 - 85% brix, $\pm 0.2\%$, Milwaukee, Rocky Mount (NC), United States), which measures the refractive index (n [brix]). Eventually, to get the weight concentration the calibration curve equation is applied. Table 1 reports in a synthetic form the instrumentation deployed.

Table 1 Instrumentation deployed.

Instrument	#	Name, range, accuracy	Producer
Thermo-resistance	4	RTD Pt100 IEC751 cl.A	Smeri
Flowmeter	1	PromagP300, 0 - 100 l/min, $\pm 0.5\%$ r.v.	Endress Hauser
Flowmeter	1	HTLD-MAG, 0 - 100 l/min, $\pm 0.5\%$ f.s.	Smeri
Refractometer	1	MA871, 0 - 85% brix, $\pm 0.2\%$	Milwaukee

2.3. Test protocol and operating conditions

The experimental conditions analyzed in this work are reported in Table 2. Specifically, 4 initial concentrations, 5 flowrates and 6 regeneration temperatures are assessed.

The procedure implemented, starting from only-water tank, is here reported:

1. Add the required mass of polymer to obtain the chosen concentration (wt./wt.).
2. Obtain a homogeneous concentration by re-circulating the solution.
3. Check the concentration by measuring the refractive index, 3 samples are extracted:
 - a. storage tank
 - b. water-rich branch
 - c. polymer-rich branch
4. Once the correct concentration is achieved, adjust the flow rate to the desired value.
5. Activate the modular resistance and adjust it to achieve the precise temperature setting.
 - a. Check that T_{reg} , T_{rich} and T_{poor} are equal.
6. Adjust the flow rate on the polymer-poor side (F_{poor}) using the valve located at the coalescer's output. F_{poor} should match, within the margin of error, a target value calculated using the lever rule, based on T_{reg} , c_{in} and the polymer's LCST curve.
7. Collect three samples each of the rich and poor solutions, allowing a 15-minute interval between each sampling. Perform three concentration measurements on each sample.
8. Measure the refractive index three times once the samples are at 20 °C.
9. Modify either flowrate or temperature and repeat (5 – 7), ensuring that T_{cooler} remains below 40 °C (i.e., lower than LCST) to ensure a single-phase fluid at the start of the process for each initial concentration tested.

Table 2. Operating conditions.

c_{in} [-]	F [l/min]	T_{reg} [°C]
		55
0.30	4	60
0.40	6	65
0.50	8	70
0.60	10	75
	12	80

Due to technological limitations, some combinations of experimental conditions are not tested. Specifically, at low flow rate and high temperature there is a very high risk of overheating the system. Whereas at high temperature and high flow rate the experimental apparatus cannot ensure steady-state conditions.

As already stated in Section 1, the main goal of the experimental campaign is to identify the influence of: (1) regeneration temperature (T_{reg}), (2) initial fluid concentration (c_{in}), (3) residence time

(τ), on the efficiency of separation for a coalescer. The residence time is defined as the ratio of the inner coalescer volume to the total flow rate.

2.4. Data processing

The coalescer separation efficiency is defined as:

$$\varepsilon = (c_{in} - c_{exp,poor}) / (c_{in} - c_{th,poor}) \quad (1)$$

indicating the coalescer's capacity to achieve the theoretically obtainable concentration (as determined by the phase diagram) in comparison to the concentration obtained experimentally.

The modeling performance is evaluated against the experimental values using the Mean Relative Deviation (*MRD*) and Mean Absolute Relative Deviation (*MARD*), defined as follows:

$$MRD = \frac{1}{N} \sum_{i=1}^N \frac{z_{i,exp} - z_{i,th}}{z_{i,exp}} \quad (i) \quad \text{and} \quad MARD = \frac{1}{N} \sum_{i=1}^N \frac{|z_{i,exp} - z_{i,th}|}{z_{i,exp}} \quad (ii) \quad (2)$$

3. Experimental results and discussion

This section provides a summary of the results from the experimental campaign and characterizes the performance of the coalescer as a function of the operating conditions.

3.1. Concentration measurements

Considering an initial concentration of 0.40, the concentrations for the water-rich side (c_{poor}), results are presented as a function of the total flow rate and regeneration temperature in Figure 3 (a).

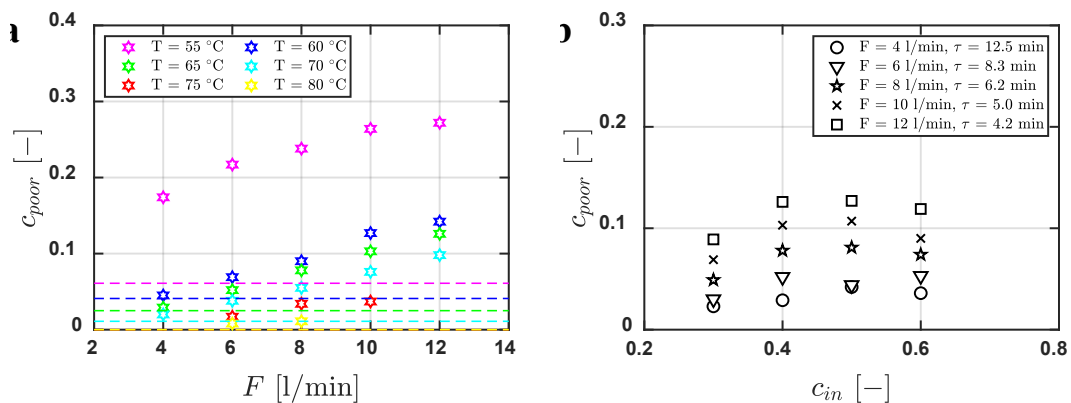


Figure 3. (a) c_{poor} having $c_{in} = 0.40$ and (b) c_{poor} vs. c_{in} at $T_{reg} = 65$ °C.

The results indicate that the regeneration temperature is likely the most significant parameter for achieving high-quality separated phases; at elevated temperatures, the concentrations rapidly approach the theoretical values. (dashed lines in Figure 3 (a)).

Finally, the initial polymer concentration appears to have a minimal impact on the separation process across the four tested conditions (c_{in}) at fixed flowrate (Figure 3 (b)).

Figure 4 graphically summarizes the results of the experimental campaigns, presenting the concentrations of the water-rich phase (left side of the charts) and polymer-rich (right side of the charts) measured relative to the LCST [11]. The charts also include error bars indicating measurement uncertainty, consistently ranging from ± 0.002 to ± 0.02 . Having the concentration a limited impact on the process performance, only one condition is plotted (i.e., $c_{in} = 0.40$).

Ultimately, it is observed that phase separation closely aligns with the LCST curve for the given case when a high regeneration temperature (above 65 °C) is selected. These results demonstrate the excellent performance of the separation process.

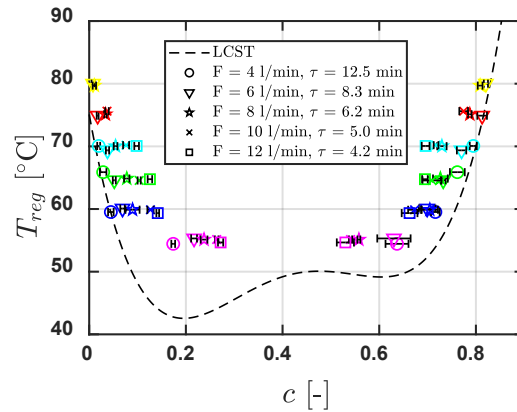


Figure 4. c_{poor} and c_{rich} measured vs. PAGB2000 LCST [11], at different T_{reg} , τ and $c_{in} = 0.40$.

3.2. Coalescer efficiency

Collecting the experimental concentrations outcomes and applying Equation (1), it is possible to determine the efficiency values (Table 3), which are then analyzed as function of both regeneration temperature and residence time at fixed initial concentration (see Figure 5). The values indicate that the coalescer operating temperature should exceed 70 °C, which is suitable for the intended application (i.e., in advanced power cycles, heat is typically rejected at around 80 °C). Furthermore, at temperatures above 70 °C and flow rates below 10 l/min, efficiency can exceed 95%.

Table 3. Efficiency values (ε) according to Equation (1).

T_{reg} [°C]	F [l/min]	c_{in} [-]				T_{reg} [°C]	F [l/min]	c_{in} [-]			
		0.30	0.40	0.50	0.60			0.30	0.40	0.50	0.60
55	4	51.8%	67.5%	75.0%	78.1%	60	4	99.5%	99.9%	98.3%	99.3%
	6	38.4%	54.0%	64.5%	73.6%		6	91.2%	92.6%	94.0%	95.0%
	8	36.1%	48.0%	57.2%	69.8%		8	83.1%	87.0%	87.1%	88.9%
	10	26.5%	40.3%	51.8%	65.1%		10	59.4%	76.6%	80.1%	84.5%
	12	17.5%	38.1%	48.2%	59.4%		12	56.0%	72.7%	78.6%	82.7%
65	4	100.0%	98.7%	96.8%	98.5%	70	4	99.1%	98.1%	98.7%	99.6%
	6	98.7%	93.5%	96.3%	95.2%		6	97.4%	93.9%	93.5%	93.2%
	8	91.4%	86.4%	88.1%	91.7%		8	94.1%	89.2%	89.8%	93.6%
	10	84.4%	79.7%	83.4%	88.9%		10	89.6%	83.4%	85.2%	86.5%
	12	76.8%	73.6%	78.8%	83.6%		12	86.4%	77.9%	81.8%	86.6%
75	6	96.4%	95.7%	91.9%	95.5%	80	6	97.6%	98.1%	98.0%	97.9%
	8	95.5%	91.6%	94.0%	94.0%		8	97.1%	97.4%	98.0%	97.6%
	10	92.0%	90.8%	91.7%	94.1%						

Once the efficiency is determined, a mathematical expression to calculate the coalescer performance as function of the above-mentioned quantities is proposed. Specifically, the expression is an exponential function developed starting from mass-exchangers efficiency, reported in [12]:

$$\varepsilon = 1 - C_1(c_{in}) \exp \left\{ \frac{C_2(c_{in})}{\tau} - C_3(c_{in})T^* \right\} \quad (3)$$

where τ is the residence time and T^* is the dimensionless temperature defined as:

$$T^* = \frac{T_{reg} - LCST(c_{in})}{T_{max} - LCST(c_{in})} \quad (4)$$

having fixed $T_{max} = 85 \text{ }^\circ\text{C}$ to account for all the regeneration temperatures measured.

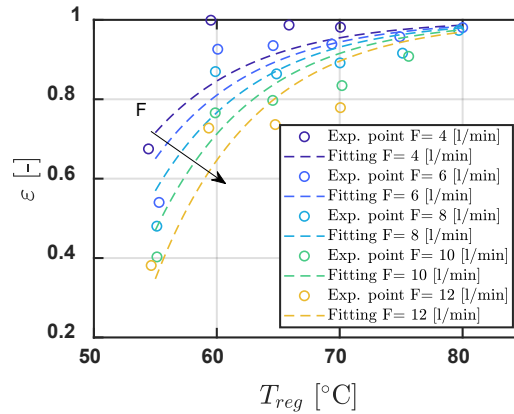


Figure 5. Efficiency vs. Regeneration Temperature at different flowrates for $c_{in} = 0.40$.

This expression incorporates the key control variables of the coalescence process: regeneration temperature, residence time, and initial concentration. Ultimately, the proposed equation aligns with the physics of the phenomenon and exhibits a monotonic trend from a mathematical perspective, approaching a value of 1 within the experimental domain considered.

A code developed with Matlab® was used to analyze the results and calculate the three fitting constants, that are function of the initial solution concentration.

The presented fitting model demonstrates reliability, with all cases showing $R^2 > 0.80$ and both *MRD* and *MARD* falling within the $\pm 10\%$ range.

Eventually, it results that the three fitting constants are independent of the initial concentration, hence the median value is chosen for each constant. Heading to, an efficiency expression equal to:

$$\varepsilon = 1 - 0.32 \exp\left\{\frac{5.05}{\tau} - 4.29T^*\right\} \quad (5)$$

4. Conclusions

- The study aimed to assess the effectiveness of a coalescer for liquid-liquid separation in a forward osmosis (FO) plant.
- The coalescer reduces energy consumption during the separation of a water-rich stream from the draw agent, particularly with a thermo-responsive material.
- The thermo-responsive polymer PAGB2000 was selected, based on previous research showing its ability to produce pure water with low energy requirements.
- Experiments evaluated the coalescer under varying conditions: initial solution concentrations, regeneration temperatures, and flow rates.
- Results showed separation efficiencies above 90% in most cases, regardless of initial concentration.
- Efficiency was significantly affected by regeneration temperature and flow rate/residence time.
- An expression for mass exchanger efficiency was derived from the findings.
- Future research will test performance with alternative thermo-responsive draw agents and metal meshes.

5. References

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Nomenclature

c	Concentration	[kg/kg]	reg	Regeneration	
F	Flowrate	[l/min]	th	Theoretical	
n	Refractive index	[Brix]	rich	Polymer-rich/ Water-poor	
T	Temperature	[°C]	ε	Efficiency	[-]
cooler	Air cooler		τ	Residence time	[min]
in	Inlet/Tank		ρ	Density	[kg/m ³]
exp	Experimental		MRD	Mean Relative Deviation	
poor	Polymer-poor/ Water-rich		$MARD$	Mean Absolute Relative Deviation	

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