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Effects of Operating Conditions on Permeate Flux and Removal Efficiency of Membrane Distillation in Semiconductor Wastewater Treatment

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Abstract

The semiconductor industry is currently facing a major challenge in treating wastewater that contains high concentrations of pollutants and a complex composition. The study focuses on evaluating the effectiveness of membrane distillation (MD) technology in treating semiconductor wastewater by investigating the influence of operating parameters – including feed temperature (40–80 °C) and flow rate (200–400 mL/min) on permeate flux, pollutant removal efficiency, and the concentration factor of the system. Experimental results show that feed temperature is the dominant factor controlling the increase in permeate flux, with the optimal operating condition occurring at a temperature of 60 °C and a flow rate of 300 mL/min. The MD technology effectively removes the characteristic pollutants, including organic matter, NO_3^-, PO_4^{3-}, and SiO_2, with removal efficiencies maintained above 95%. In particular, for multivalent anions such as PO_4^{3-}, the separation process exhibits very high effectiveness, with removal efficiency reaching nearly 99%, while the concentration factor attained is 2.3. This study provides an initial assessment of the potential of MD technology for clean-water recovery, concentration, and efficient resource reuse from the semiconductor industry.

Keywords: Circular economy, membrane distillation, reuse, semiconductor, wastewater treatment

1. Introduction

The semiconductor industry encompasses research and development, design, manufacturing, packaging, and testing of semiconductor products, as well as the production of the equipment, machinery, and tools that serve these manufacturing activities [1]. Semiconductors are materials with partial electrical conductivity, allowing electric current and signals to be controlled flexibly. This not only enables the creation of complex integrated circuits but also supports the development of high-technology products [2], such as traffic management systems, healthcare, and national defense and security. These applications are the driving force behind the future growth of the semiconductor industry [3].

The strong development of the semiconductor industry has increased competitiveness in the global industrial landscape [4]. Global revenue is projected to reach approximately USD 700 billion by 2025 and to exceed USD 1,000 billion by 2030 [5], with a CAGR (Compound annual growth rate) sustained at 7.7% over the 2020–2030 period [6, 7].

In Vietnam, this development has been strongly driven by government policies and initiatives, combined with the presence of multinational technology corporations such as Nvidia, Amkor, and Samsung [8], along with the initial establishment of domestic manufacturing capacity – exemplified by the Viettel Semi chip manufacturing plant inaugurated in January 2026. The semiconductor market in Vietnam reached a revenue of approximately USD 21 billion in 2025 [9].

Behind the strong development of the entire semiconductor industry lies a foundation built upon semiconductor component manufacturing technology – an ensemble of some of the most complex processes that humankind has successfully carried out at large scale. This fabrication stage revolves around four main steps: deposition, photolithography, etching, and ion implantation, all aimed at creating microscopic circuit structures with feature sizes measured in nanometers [10, 11].

Although it delivers high technological value, the semiconductor component manufacturing process also entails a challenge: the generation of industrial wastewater streams containing complex pollutant components that are released into the environment. The stage that generates the most wastewater during manufacturing is the etching, chemical-mechanical polishing, and cleaning/rinsing of wafers. Depending on the chemical properties of the chemicals used in production, the discharge is classified into four main streams: (1) HF acid wastewater; (2) acidic, alkaline, and organic wastewater; (3) wastewater from the CMP (Chemical mechanical polishing) stage; and (4) waste

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with high organic concentrations [12]. Studies have shown that the composition of semiconductor wastewater contains perfluorooctanoic acid, Tetramethylammonium hydroxide (TMAH), CaF_2, KOH, NH_3–N, turbidity, pH variations, total solids (TS), total suspended solids (TSS), chemical oxygen demand (COD), sulfate, and others [12].

Owing to the complex characteristics of these pollutant components, several advanced treatment technologies are currently being applied. Among the technologies mentioned above, membrane distillation (MD) offers outstanding advantages, including: the ability to remove nearly all dissolved solutes, operation at ambient pressure, and the ability to utilize waste heat from production. Although MD faces limitations such as fouling, membrane wetting, and high energy consumption, this technology is still a good choice because of its optimal clean water recovery efficiency and its capability to effectively separate waste streams containing highly persistent compounds, which conventional technologies or ordinary membrane systems are not yet able to treat.

MD is a thermally driven process that exploits the selective permeability of a hydrophobic membrane to facilitate the transport of water vapor. The transport process is driven by the vapor pressure gradient generated by the temperature difference across the membrane surface [13]. MD operates effectively in the low-temperature range (30–80 °C), allowing the recovery of low-grade heat and thereby reducing energy consumption [14], together with a simple configuration, compatibility with a wide range of feed liquids, and the absence of auxiliary components such as condensers, blowers, or vacuum pumps [15].

Among the different MD configurations, DCMD is particularly attractive because of its simple and compact configuration, with the feed and permeate streams directly contacting the two sides of the hydrophobic membrane. Unlike vacuum MD (VMD) and air gap MD (AGMD), direct contact MD irect contact membrane distillation (DCMD) does not require an additional vacuum system or air gap, making it suitable for evaluating the effects of feed temperature and flow rate on permeate flux and removal efficiency. Therefore, DCMD is particularly appropriate for downstream polishing and water recovery of pretreated semiconductor wastewater. Fig. 1 illustrates the operating principle of MD technology.

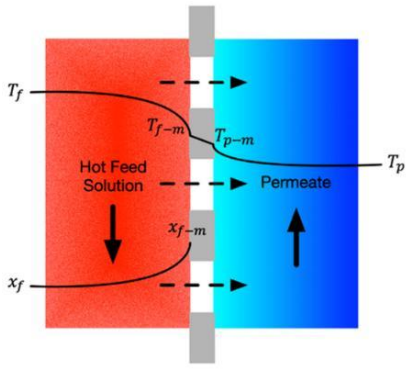


Fig. 1. Operating principle of DCMD

DCMD is a treatment process that removes pollutants based on thermal and physical separation processes. Many factors can influence the performance of the treatment process, such as temperature, flow rate, or membrane characteristics [16, 17].

Table 1. Selected MD operations for wastewater treatment and recovery

MD configuration	Wastewater source	Temperature (°C)	Flux (L/m²·h)	Permeate quality
DCMD	Petrochemical	Feed: 56.8–58.2; Permeate: 29.5–33.7	8.3–10.9; decreasing to 4.9–7.0 after 156 h	TDS removal: > 95%; TOC removal: > 80%; Turbidity removal: > 81%
DCMD	Synthetic oilfield	Feed: 65; Permeate: 30	13; decreasing to 1.3 after 10 h	–
AGMD	Boron-containing wastewater	Feed: 70; Permeate: 25	20–160, depending on membrane type	Boron removal: > 99%
VMD	Radioactive	Feed: 70–90; Permeate: –	1.59–6.82, depending on feed temperature	Cs decontamination factor: $10^{4.85}$; concentration factor: 110.3
DCMD	Aquaculture	Feed: 60; Permeate: 20	19.1 (PP/HV); 7.3 (PP/LV)	Salt-ion removal: > 99%
DCMD	Textile	Feed: 40, 60, 80; Permeate: 20	15–53; decreasing to a maximum of 20 after 13 h	Color removal: 100%
DCMD	Olive mill	Feed: 30–60; Permeate: 20	5.6–7.7; decreasing to 3.5–7 after 3 h and to 1.4 after 30 h	Phenol separation factor: 99%

Table notes: Direct Contact Membrane Distillation (DCMD); Air Gap Membrane Distillation (AGMD); Vacuum Membrane Distillation (VMD)

Optimal control of the operating parameters plays a decisive role in the feasibility and scalability of MD technology in practice. Table 1 describes the membrane distillation configurations used to treat the characteristic wastewater of each industry.

Although most studies on MD technology remain at the laboratory scale, its distinctive advantages have motivated several pilot-scale applications, including the treatment of wastewater from a power plant in Singapore, the treatment of wastewater at a chemical plant in the Netherlands operated by Memstill, and various other industrial wastewaters [18]. Various MD configurations, such as DCMD and air gap membrane distillation (AGMD), have also been investigated using simulated wastewater and pretreated real wastewater by research institutes and universities worldwide. These developments highlight the potential of MD for treating semiconductor wastewater, particularly for recovering clean water and removing difficult-to-treat pollutants in an industry with high demand for ultrapure-water. However, the application of MD to semiconductor wastewater remains relatively limited. Therefore, this study systematically evaluates DCMD for pretreated semiconductor wastewater by investigating the effects of feed temperature and flow rate on permeate flux, pollutant removal efficiency, and concentration factor. The novelty of this work lies in identifying an optimal operating condition within the investigated range based on the combined assessment of water production, pollutant removal, and concentration performance, rather than maximizing permeate flux alone.

2. Materials and Methods

2.1. Materials

This study was conducted to evaluate the influence of selected operating parameters on the removal performance for several typical pollutants, in service of the goal of resource recovery and reuse from the semiconductor industry. The objectives include:

1) Evaluating the influence of temperature and flow rate on the permeate flux of the MD membrane.
2) Evaluating the influence of temperature and flow rate on the removal efficiency and recovery ratio of COD, NO_3^-, PO_4^{3-}, and SiO_2 of the MD membrane.
3) Determining the optimal operating conditions that balance water recovery capability with pollutant removal of the MD membrane.

The subject of this study is a DCMD technology system that uses a flat-sheet hydrophobic PTFE membrane material. The technical specifications of the membrane are presented in Table 2.

The object of investigation is the semiconductor wastewater stream generated from a typical semiconductor component manufacturing stage, which carries complex pollution characteristics such as silica, heavy-metal ions, organic solvents, and high nutrient concentrations.

The scope of the study is limited to the laboratory scale, in order to evaluate the water-recovery and treatment performance of the system through its polluting parameters. The experiments aim to verify operational stability under continuous operation over a given period of time. The assessments focus on the removal efficiency of the main pollutants such as COD, NO_3^-, PO_4^{3-}, and SiO_2, in order to evaluate the quality of the recovered water as well as the ability to concentrate the feed stream for the purpose of recovering nutrients and other pollutants.

Table 2. Membrane specifications

Parameter	Value
Supplier	Sterlitech, USA
Model	CF016A
Type	Hydrophobic membrane
Active layer	PTFE
Support layer	Polypropylene (PP)
Pore size (μm)	0.45
Contact angle (°)	110–120
Maximum temperature (°C)	88
Effective filtration area (m²)	0.00206 (= 20.6 cm²)

The DCMD system comprises two main processes: a separation process in which water vapor is separated from the feed wastewater via temperature being applied across the hydrophobic membrane, and a condensation process in which the separated water vapor is condensed to recover clean water [19]. Fig. 2 describes the proposed DCMD system setup, comprising the components shown below.

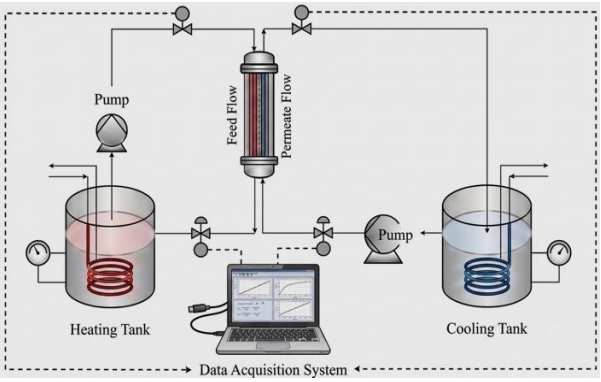


Fig. 2. DCMD system setup

The system includes i) feed tank: where the wastewater fed into the MD system is stored; ii) permeate-vapor tank: where the water vapor drawn

out by the pump is collected; iii) heating device: heats the wastewater in the feed tank and maintains the temperature difference between the feed and permeate sides of the membrane; iv) peristaltic pump: creates the osmotic-pressure environment on the permeate side of the membrane to promote the transport of water vapor from the feed to the membrane surface; v) feed chamber: where the wastewater directly contacts the hydrophobic membrane; vi) permeate chamber: where the water vapor is condensed and drawn out by the pump; vii) membrane: the core component of the MD system; its hydrophobic property allows the permeation of water-vapor molecules but does not allow larger solutes to pass.

2.2. Methods

The analytical methods employed in this study included chemical oxygen demand (COD) determination according to TCVN 6491:1999, nitrate (NO_3^-) determination according to TCVN 6180:1996, phosphate (PO_4^{3-}) determination according to TCVN 6202:2008, and silicon dioxide (SiO_2) determination using the 4500-SiO_2 C Molybdosilicate Method. The pH and electrical conductivity (EC) were measured using an 86554 AZ Benchtop pH & EC Printer (AZ Instrument Corp., Taiwan). UV–Vis spectrophotometric analyses were performed using a UV-2700 UV–Vis spectrophotometer (Shimadzu, Japan), while COD digestion was conducted using a DRB200 Tubetests Heater Digital COD Digester (Hach, USA).

The research results will characterize the wastewater and the membrane material used, while also investigating the operating factors in order to evaluate the clean-water recovery capability of the MD system. These experimental results serve as an important premise for proposing wastewater treatment at a larger scale, with the aim of recovering valuable water for agricultural or industrial use, thereby realizing a circular-economy model in semiconductor wastewater treatment.

The permeate flux value (J) is determined by the following formula:

$$J = \Delta m / (A \cdot \Delta t) \quad (1)$$

where:

Δm - mass of water collected (kg)

A - effective membrane area (m^2)

Δt - treatment time (h)

3. Results and Discussion

3.1. Characteristics of the Semiconductor Wastewater used for membrane distillation

In this study, the wastewater investigated was semiconductor wastewater generated from typical semiconductor component manufacturing processes and characterized by a complex pollutant composition, including silica, heavy metal ions, organic solvents, and high nutrient concentrations. The initial composition of the semiconductor wastewater included SiO_2 (20 mg/L), glucose (351 mg/L), NH_4Cl (23.4 mg/L), KH_2PO_4 (6 mg/L), $MgSO_4 \cdot 7H_2O$ (13 mg/L), $FeSO_4 \cdot 7H_2O$ (13 mg/L), $CaCl_2 \cdot 2H_2O$ (13 mg/L), and other trace nutrients. The semiconductor wastewater was pretreated using a microalgae system combined with a membrane, and the effluent from this pretreatment system was subsequently used as the feed stream for the MD system. The input data for the MD system are presented in Table 3.

Table 3. Influential parameters and concentrations of the semiconductor wastewater fed to the MD system

Parameter	Unit	Concentration	QCVN 40:2025/BTNMT (Column B)
pH	–	5.25 ± 0.25	6–9
EC	µS/cm	512 ± 20	–
COD	mg/L	166.67 ± 8.5	≤ 90
NO_3^-–N	mg/L	41.86 ± 0.14	T–N ≤ 40
PO_4^{3-}–P	mg/L	6.865 ± 0.635	T–P ≤ 6
SiO_2	mg/L	27.57 ± 3.13	–

The wastewater entering the MD system was pretreated semiconductor wastewater obtained after treatment by the MPBR (microalgae photomembrane bioreactor) system. The characterization of this pretreated wastewater showed that its quality still did not meet the requirements of QCVN 40:2025/BTNMT (Column B), because the pH and COD indices, as well as the nutrient concentrations (NO_3^-, PO_4^{3-}), all exceed the limit thresholds. The presence of SiO_2 together with an electrical conductivity of about 512 µS/cm indicates a high risk of membrane fouling due to inorganic scaling, as well as the potential to recover and reuse these polluting components. Therefore, this pretreated semiconductor wastewater was selected as the feed for MD to further evaluate its polishing and water-recovery potential.

3.2. Investigation of the Influence of Operating Factors on System Performance

3.2.1. Influence on permeate flux

Permeate flux is one of the important indicators for evaluating the performance of the MD system. In this study, the influence of the two main operating

parameters–feed temperature and flow rate–was investigated in detail in Fig. 3.

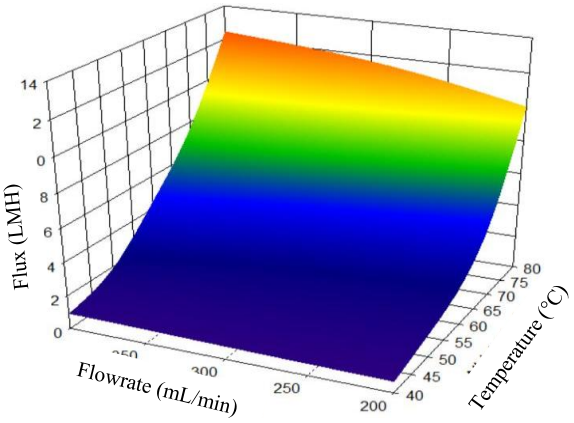


Fig. 3. Influence of temperature and flow rate on permeate flux

Based on the water permeate-flux plot, temperature is the dominant factor influencing process performance. As the temperature increases from 40 °C to 80 °C, the permeate flux increases significantly, reflected by the color gradient changing from the dark blue region (1.0 LMH) to the orange region (12.5 LMH). This phenomenon occurs because temperature plays the leading role in water-vapor generation. The increase in feed temperature is directly proportional to the amount of water vapor produced. Since the membrane's separation mechanism allows transport only of the vapor phase, the higher the water-vapor density, the greater the flux performance through the membrane.

Flow rate also has a significant effect on permeate flux; at the same temperature condition, increasing the flow rate improves the flux. For example, at a temperature of 70 °C, increasing the flow rate from 200 mL/min to 400 mL/min increased the flux from 4.91 LMH to 7.64 LMH. This increase occurs because the hot feed temperature is transferred to the membrane surface more effectively; the higher the temperature at the membrane surface, the higher the saturated vapor pressure generated, which in turn produces a vapor pressure difference across the membrane and leads to an increase in the flux value.

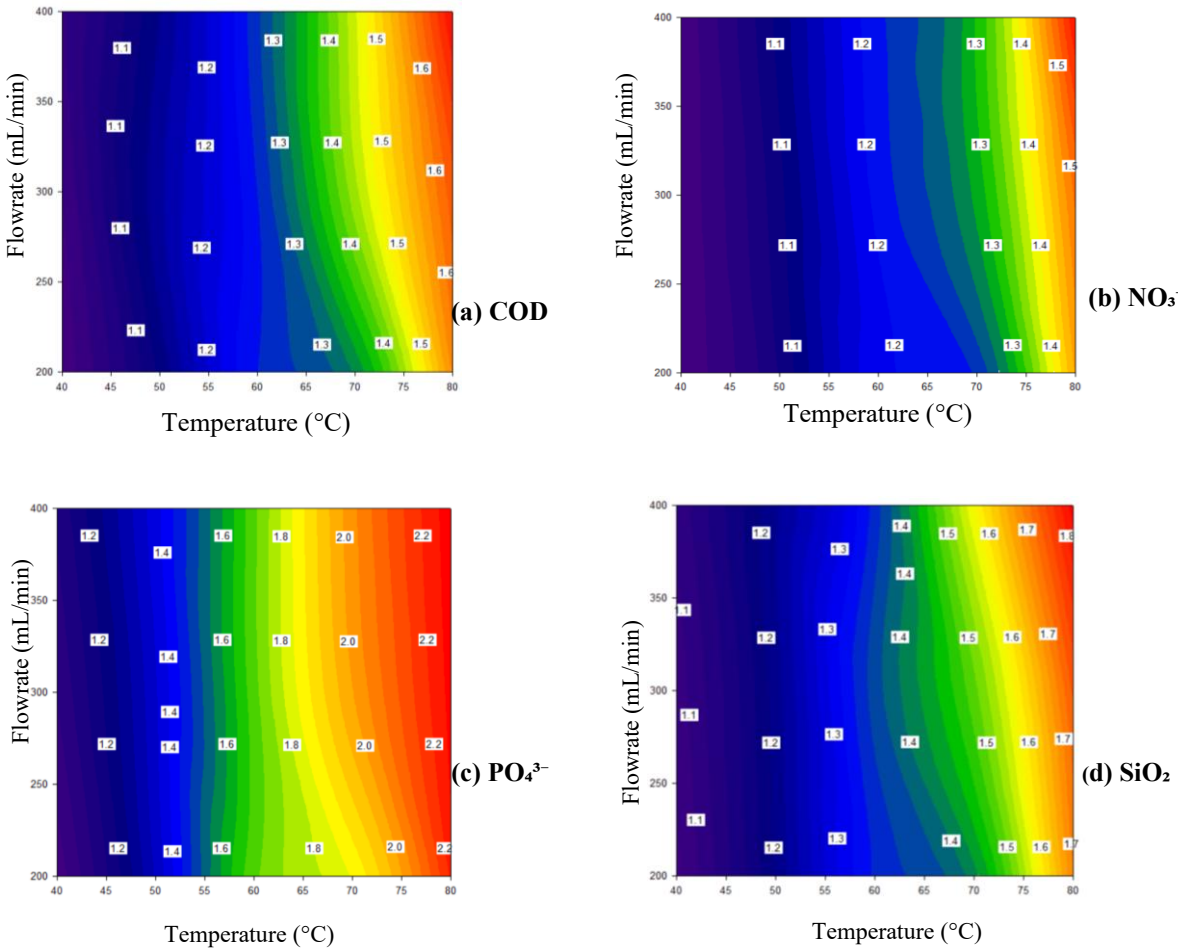


Fig. 4. Concentration factors of nutrients under the investigated conditions. (a) COD; (b) NO_3^-; (c) PO_4^{3-}; (d) SiO_2

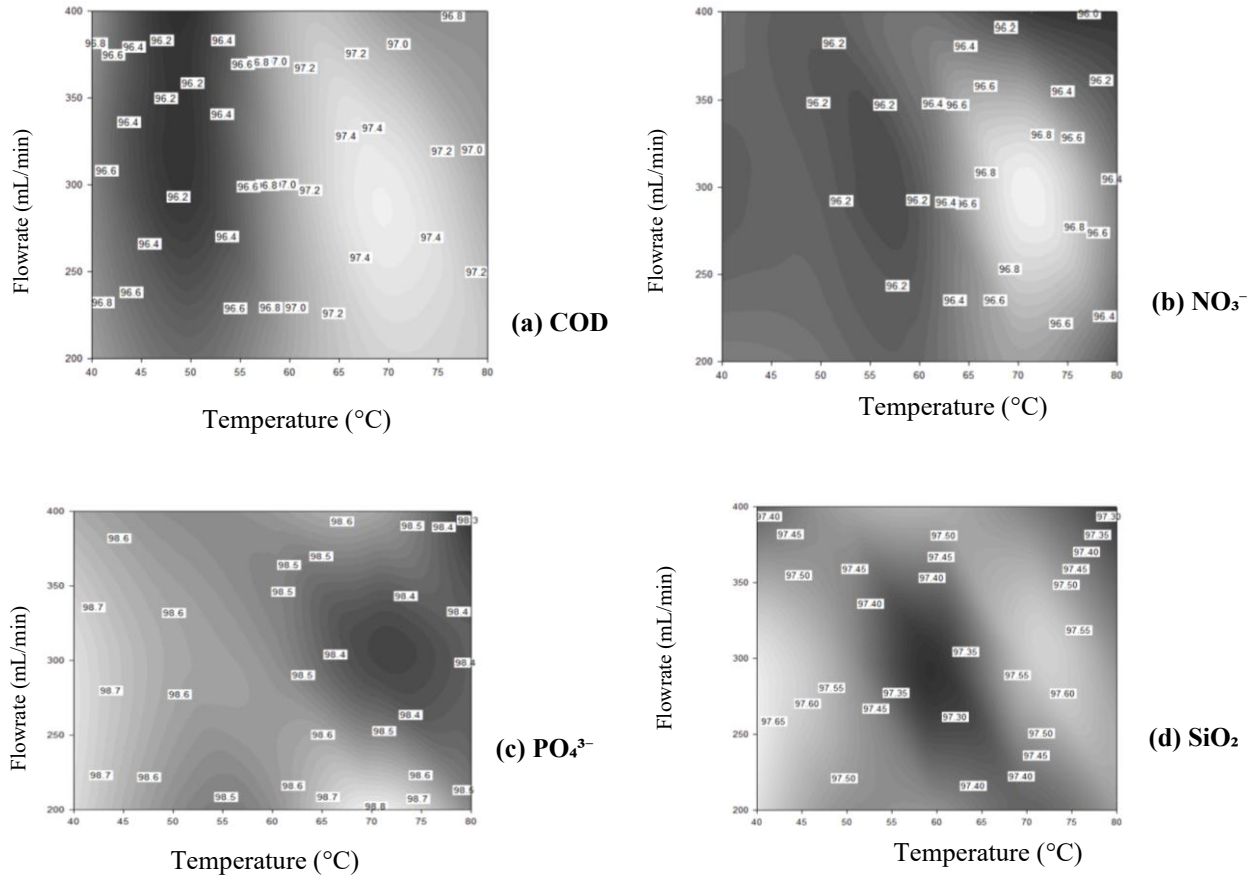


Fig. 5. Pollutant removal efficiency under the investigated conditions (a) COD; (b) NO_3^-; (c) PO_4^{3-}; (d) SiO_2

3.2.2. Influence on the concentration factor

In the chart in Fig. 4, based on the iso-value contours, it can be seen that the concentration factor is directly proportional to the increase in feed temperature. In the lower temperature range of 40–60 °C, this index shows linear growth, with the degree of concentration reaching a high value at 60 °C, with the concentration factor ranging from 1.25 to 1.7. In the higher temperature range of 70–80 °C, the concentration process is strongest. At 80 °C, thanks to the maximum permeate flux, the large amount of water evaporating from the feed stream leads to a sharp increase in the concentration factor, reaching about 2.23 for the PO_4^{3-} parameter (Fig. 4c) – the highest among all analyzed parameters. The high removal efficiency of PO_4^{3-} can be primarily attributed to the vapor-phase transport mechanism of MD, which strongly restricts the passage of non-volatile dissolved species through the hydrophobic membrane. In addition, membrane surface charge also contributes to the rejection of ionic species through electrostatic interactions. A negatively charged membrane surface potentially induces electrostatic repulsion against anions, and this effect may be more pronounced for multivalent ions such as PO_4^{3-}, which has a valence of −3. Therefore, electrostatic repulsion is considered a possible contributing factor to the high PO_4^{3-} removal observed. Other parameters such as COD, NO_3^-, and SiO_2 also recorded an increase in concentration, reaching values of about 1.70, 1.59, and 1.83, respectively, at the highest temperature and flow-rate operating condition.

In addition, the concentration factor tends to increase progressively as the flow rate increases, most clearly at the high-temperature levels of 60–80 °C. Increasing the flow rate helps optimize the mass-transfer process; the saturated vapor pressure is maintained at a stable level, promoting a stronger water-vapor flux through the membrane and thereby accelerating the accumulation rate of solutes in the feed stream.

3.2.3. Influence on removal efficiency

Rejection efficiency–the removal of pollutants–is the core criterion for evaluating the treatment effectiveness of the hydrophobic membrane in MD technology. Experimental results show that the removal efficiency reaches very high values for the solutes in the feed stream. In the chart in Fig. 5, the analysis results show that the system maintained consistently high pollutant removal efficiencies, with only minor variations among the different operating conditions investigated (> 96%).

The removal efficiency of organic matter measured as COD ranges from 96.2% to 97.4% (Fig. 5), while the inorganic components show even better removal. In particular, the PO_4^{3-} separation efficiency reaches the highest value, up to nearly 99% (Fig. 5), followed by SiO_2

(~97.7%) and NO_3^- (~96.9%). The reason is that the non-volatile nature of the inorganic pollutants during distillation leads to the highest separation efficiency for these substances.

Notably, unlike the permeate flux–which is usually sensitive to temperature variation–the removal efficiency of this process is little affected by changes in feed temperature and flow rate, because the removal efficiency is governed mainly by the non-volatility of the solutes and the hydrophobicity of the membrane, and depends little on operating parameters such as temperature or flow rate. Accordingly, the iso-value contours show that the variation in value is negligible.

3.2.4. Optimal operating conditions

Specifically, the operating point at a temperature of 60 °C and a flow rate of 300 mL/min is evaluated as the best operating condition, ensuring a balance among treatment performance, waste-stream concentration ratio, treated-water quality, and – in particular – the optimization of energy consumption for operation.

When the system is operated at a temperature of 60 °C and a flow rate of 300 mL/min, the water permeate flux reaches about 3.0 LMH. The recovered clean water originates from establishing a partial vapor pressure difference across the two sides of the membrane surface, thereby shortening the mass-transfer time and maximizing the water-separation efficiency of the MD process.

Operating temperature is the parameter that directly determines the volumetric concentration factor of the system. At the optimal operating condition of 60 °C and a flow rate of 300 mL/min, the phase-change process proceeds strongly, helping the concentration factor reach a high level; for example, the concentration of the PO_4^{3-} parameter increases by a factor of 1.7. The concentration-factor value reflects the membrane's effectiveness in separating the waste stream: it both maximizes the amount of clean water and recovers nutrients.

In terms of treatment effectiveness, setting up the system at the optimal operating condition of 60 °C and a flow rate of 300 mL/min does not reduce the membrane's selectivity at all. On the contrary, the good treatment results are reflected in the removal efficiency of the semiconductor wastewater pollution indicators (including COD, NO_3^-, PO_4^{3-}, and SiO_2), which are always maintained stably at a very high level (above 96%). The results show that, under the optimal operating condition, the membrane's hydrophobicity is still maintained, membrane wetting is controlled, and the stability of the phase-change process is ensured.

The operating condition of 60 °C and a flow rate of 300 mL/min is the optimal treatment condition, allowing the system to operate at high capacity with the best pollutant concentration capability, meeting the requirements for resource recovery and waste-stream volume reduction, and – in particular – optimizing the energy consumed for operating the MD system.

4. Conclusion

This study is oriented toward the application of MD technology in the treatment of semiconductor industrial wastewater. The results show MD is a promising treatment solution that meets two core objectives: clean-water recovery and the concentration of nutrients and resources for reuse, thereby reducing the waste-stream volume. The system's effectiveness depends on the operating conditions, among which feed temperature is the main factor directly influencing the increase in permeate flux and concentration factor. The results have demonstrated the treatment capability of MD technology in removing almost completely the non-volatile solutes and inorganic compounds, achieving especially high treatment efficiency for anions. The results also indicate the optimal conditions to treat semiconductor wastewater: a temperature of 60 °C and a flow rate of 300 mL/min.

These initial research results provide an important basis for expanding studies on the practical application of MD to complex industrial wastewater. Accordingly, future studies should focus on evaluating long-term membrane stability, investigating wetting resistance, and evaluating membrane fouling under long-term operating conditions. Further research on membrane material modification and system optimization is also needed to improve operational stability and treatment performance. In addition, after studying the influencing factors at the laboratory scale, the research can be scaled up to the pilot scale and tested directly on real semiconductor wastewater, contributing to the goal of sustainable development in Vietnam's industrial sectors.

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