INFLUENCE OF OPERATIONAL PARAMETERS ON THE EFFICIENCY OF FORWARD OSMOSIS DESALINATION SYSTEMS USING POLYVINYLPYRROLIDONE K17

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***Hoang Minh Tao** [* 1,2], **Nguyen Quang Trung** [1], **Nguyen Ngoc Tung** [1], **Bui Quang Minh** [1], **Trinh Tuan Hung** [1], **Nguyen Thị Hoai Thu** [1], **Hoang Thi Thoa** [1]*

[1] Graduate University of Science and Technology, Vietnam Academy of Science and Technology

[2] Center for High Technology Research and Development, Vietnam Academy of Science and Technology

** Email: htm1205@gmail.com*

TÓM TẮT

ẢNH HƯỞNG CỦA CÁC ĐIỀU KIỆN VẬN HÀNH LÊN HIỆU QUẢ HOẠT ĐỘNG CỦA HỆ THỐNG LỌC THẨM THẤU XUÔI SỬ DỤNG CHẤT LÔI CUỐN POLYVINYLPYRROLIDONE K17

Công trình này khảo sát ảnh hưởng của các yếu tố điều kiện vận hành lên hiệu quả hoạt động của hệ thống khử mặn trên cơ sở công nghệ lọc thẩm thấu xuôi sử dụng chất lôi cuốn Polyvinylpyrrolidone K17. Các yếu tố điều kiện vận hành được khảo sát bao gồm: chênh lệch áp suất giữa dung dịch cần xử lý và dung dịch lôi cuốn, lưu lượng dòng vào, nhiệt độ dòng vào, và hướng di chuyển tương đối giữa dòng dung dịch cần xử lý và dòng dung dịch lôi cuốn tại hai phía của màng bán thấm. Ảnh hưởng của các yếu tố điều kiện vận hành này lên hiệu quả hoạt động của hệ thống lọc thẩm thấu xuôi được đánh giá thông qua sự thay đổi của giá trị thông lượng nước thẩm thấu qua màng và giá trị thông lượng chất lôi cuốn thẩm thấu ngược qua màng. Kết quả khảo sát cho thấy, tồn tại những mối quan hệ nhất định giữa các yếu tố điều kiện vận hành và hiệu quả hoạt động của hệ thống lọc thẩm thấu xuôi. Điều này nhấn mạnh sự cần thiết của việc phải tối ưu hoá các yếu tố điều kiện vận hành nhằm giúp hệ thống khử mặn trên cơ sở công nghệ lọc thẩm thấu xuôi sử dụng chất lôi cuốn Polyvinylpyrrolidone K17 đạt được hiệu quả sản xuất nước ngọt cao nhất.

Từ khoá: *thẩm thấu xuôi, Polyvinylpyrrolidone K17, điều kiện vận hành, thông lượng nước, thông lượng chất lôi cuốn*

1. INTRODUCTION

Osmosis is a physical phenomenon in which the mass transfer of water through a semipermeable membrane is driven by the difference in pressure across the membrane. In forward osmosis processes, this driving force is specifically the difference in natural osmotic pressure between solutions on either side of the membrane, namely the feed solution and the draw solution [1]. Unlike many other desalination methods such as thermal distillation or reverse osmosis, a significant advantage of forward osmosis processes is that it does not require external energy to drive the mass transfer of water, thus leading to significant reduction in energy consumption of such desalination systems [2,3].

For this reason, in recent years, forward osmosis desalination has garnered substantial interest from researchers, primarily focusing on identifying potential novel draw solutes and modifying the materials used to fabricate the semipermeable membranes in order to improve their salt rejection capabilities [4,5]. However, those are not the only elements that can impact the fresh water production efficiency of forward osmosis desalination systems, as numerous researches have successfully proven the connection between fresh water production efficiency of forward osmosis desalination systems and their various operational parameters, which include: the difference in hydraulic pressure between two sides of the semipermeable membrane, the flow rate and the temperature of the inlet streams, and the relative flow direction difference between the feed solution stream and the draw solution stream [6].

In 2022, Nguyen Quang Trung et al. conducted preliminary studies on Polyvinylpyrrolidone K17 (hereby abbreviated as PVP K17), a promising novel draw solute for forward osmosis desalination systems, and obtained noteworthy results. Specifically, the researchers focused on investigating the impacts of draw solution concentration, feed solution salinity, and operation duration on the performance of the PVP K17 draw solution, as well as the draw solution regeneration efficiency of nanofiltration method [7].

Building on these results, this study was conducted to investigate the impacts of various operational parameters on the performance of forward osmosis desalination systems using PVP K17 as the draw solute. The investigated operational parameters include: the difference in hydraulic pressure between the feed solution and the draw solution, the flow rate of feed solution and draw solution, the temperature of feed solution and draw solution, and the relative flow direction between the feed solution stream and the draw solution stream. The effects of these operational parameters on the performance of forward osmosis desalination systems were evaluated based on the changes in water flux and reverse solute flux.

2. METHODOLOGY

2.1. Materials and Equipment

Aqueous solvent: Deionized water (salinity ≤ 5 ppm) was produced using the Direct-Q® 5 UV Remote Water Purification System (Merck, Germany) at the Center for High Technology Research and Development, Vietnam Academy of Science and Technology.

Draw solute: Polyvinylpyrrolidone K17 (analytical grade) was supplied by Sigma-Aldrich (USA).

Salt solute: Refined sea salt was supplied by Long Hai (Vietnam).

Semipermeable membrane: HFFO membranes were supplied by Aquaporin (Denmark). These were thin-film composite (TFC) flat sheet membranes with dimensions of 56 × 115 mm, and an effective filtration area of 42 cm^2.

Testing module: Forward Osmosis CF042 Cell Assembly module was supplied by Sterlitech (USA). This module was a laboratory-scale forward osmosis filtration module specifically designed for testing and evaluating the performance of forward osmosis membranes in a controlled laboratory environment.

Other auxiliary equipment and tools: Flow pumps, digital scale, integrated salinity meter, water containers, water pipes, control valves, pressure gauges, thermal control elements...

2.2. Experimental Method

In general, experiments were conducted using the setup described in the published work by Nguyen Quang Trung et al. [7]. Specifically, after performing system cleaning steps, 1,000 mL of the feed solution (deionized water or 10‰ salt solution) and 1,000 mL of 20% Polyvinylpyrrolidone K17 draw solution (hereby abbreviated as PVP 20% solution) were loaded into the respective containers. Experiments were then commenced by simultaneously starting the feed solution pump and the draw solution pump, and continued for 150 minutes. Through this duration, at 15-minute intervals, the weight of the draw solution and the salinity of the feed solution were recorded to monitor the changes in these parameters over time.

In particular, base-line operational parameters for experiments in this study were established as following:

Feed solution: 10‰ salt solution (for water flux determination) or deionized water (for reverse solute flux determination).

Draw solution: PVP 20% solution.

Inlet flow rate – Feed solution: 200 $mL \cdot min^{-1}$.

Inlet flow rate – Draw solution: Adjusted to maintain a difference in hydraulic pressure of 0.2 bar between the feed solution side and the draw solution side.

Inlet temperature – Both solutions: 30 °C.

Relative flow direction of the draw solution stream and feed solution stream: Counter-current.

Each experimental setup in this study was repeated for at least five times to ensure repeatability, with a maximum permissible differential margin in experimental results not exceeding 10%.

2.3. Methods for Result Calculation

Performance of the forward osmosis filtration system was evaluated based on two main parameters: water flux (JW), and reverse solute flux (JD). In particular, these parameters were calculated from experimental results as follows:

$$JW = (mt - m0) / (t \times A \times \rho)$$

$$JD = Ct \times (V0 - JW \times t \times A) / (t \times A)$$

where:

- **JW** was Water flux (unit: $L \cdot m^{-2} \cdot h^{-1}$, or LMH)

- **JD** was Reverse solute flux (unit: $g \cdot m^{-2} \cdot h^{-1}$, or GMH)

- **A** was the active filtration area of the semi-permeable membrane, which was 0.00042 m^2

- **ρ** was the specific density of water, which was 0.001 $g \cdot L^{-1}$

- **t** was the total operational duration of experimental system at the particular sampling point (unit: h)

- **m0** was the initial weight of the draw solution and its container (unit: g)

- **mt** was the weight of the draw solution and its container at the particular sampling point (unit: g)

- **Ct** was the concentration of dissolved solids in the feed solution at the particular sampling point (unit: $g \cdot L^{-1}$)

- **V0** is the initial volume of the feed solution, which was 1 L

3. RESULTS AND DISCUSSION

3.1. Influence of the Difference in Hydraulic Pressure

Experiments were conducted with the difference in hydraulic pressure between the feed solution inlet and the draw solution inlet ranging from 0 to 0.8 bar, in both directions. Experimental results (as shown in **Figure 1**) indicated that as the hydraulic pressure at the feed solution inlet increased and exceeded that at the draw solution inlet, the recorded value for water flux also increased. Conversely, when the hydraulic pressure at the draw solution inlet increased and exceeded that at the feed solution inlet, the recorded value for water flux exhibited significant reductions.

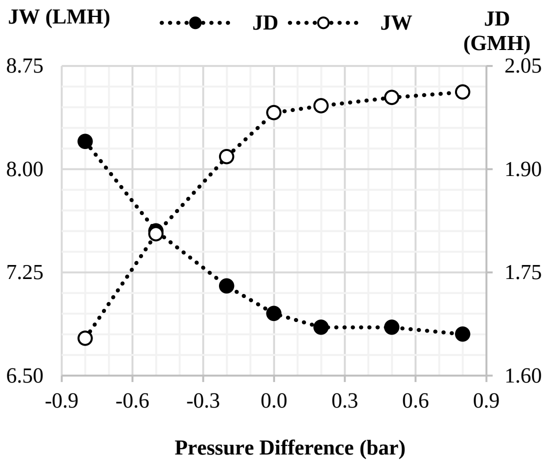

Figure 1 *Influence of the difference in hydraulic pressure on water flux (JW) and reverse solute flux (JD)*

This phenomenon can be explained by the fact that in most membrane filtration systems, which include forward osmosis desalination systems, the mass transfer of water through the semipermeable membrane is driven by the difference in pressure across the membrane. Specifically, in forward osmosis processes, this driving force is a combination of the difference in natural osmotic pressure and the difference in hydraulic pressure between the feed solution side and the draw solution side. These two types of pressure differences can either complement each other (acting in the same direction) or counteract each other (acting in opposite directions), causing corresponding changes in the value of water flux achieved [3].

Similar principle can also be used to explain changes in the value of reverse solute flux, albeit in the reversed manner.

From these results, it can be concluded that the forward osmosis filtration system using PVP K17 draw solution operated most efficiently when hydraulic pressure at the feed solution inlet was higher than hydraulic pressure at the draw solution inlet. Such difference in hydraulic pressure can lead to significant improvement in water flux, while also measurably limiting reverse solute flux. However, when the difference in hydraulic pressure between the feed solution inlet and the draw solution inlet exceeded 0.2 bar, the impact of increasing such hydraulic pressure difference became less consequential.

3.2. Influence of Inlet Flow Rate

Experiments were conducted with the flow rate at feed solution inlet ranging from 100 to 650 $mL \cdot min^{-1}$, while the flow rate at draw solution inlet was adjusted correspondingly to maintain a 0.2-bar difference in hydraulic pressure between those inlets.

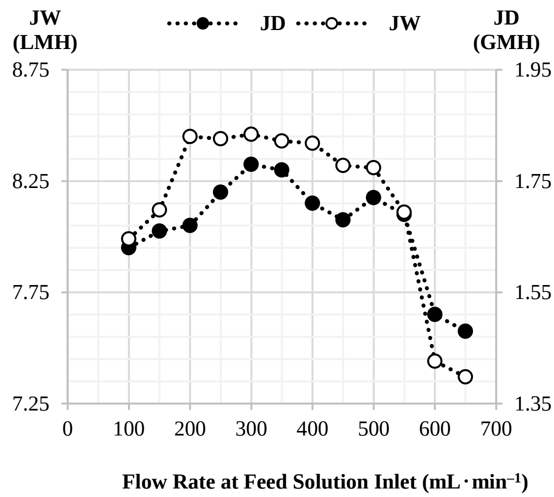

Figure 2 *Influence of inlet flow rate on water flux (JW) and reverse solute flux (JD)*

Experimental results (as shown in **Figure 2**) indicated that when the flow rate at feed solution inlet was too low (below 200 $mL \cdot min^{-1}$) or too high (above 500 $mL \cdot min^{-1}$), significant reductions in water flux were observed. This phenomenon can be explained by the fact that flow rate is an important factor determining fluid dynamics, which in turn impacts the mixing efficiency of fluid particles within the forward osmosis system

In particular, at lower flow rate, there were no cross-currents perpendicular to the direction of flow, nor eddies and/or swirls within the fluids, which limit lateral mixing between adjacent layers of the stream. In forward osmosis systems, such phenomena can lead to local concentration polarization near the surface and within the structure of the semipermeable membrane, causing significant reductions in water flux. Conversely, higher flow rate can lead to turbulent flow, which encourages lateral mixing through the increase in eddies and/or swirls within the fluids. However, as the turbulent flow becomes more violent due to heightened flow rate, local pockets of elevated and plummeted hydraulic pressure may form, de-stabilizing the mass transfer process of water through the semipermeable membrane and reducing water flux [8].

This phenomenon can also explain the observed changes in reverse solute flux in experimental results [9]. Specifically, reverse solute flux of PVP K17 draw solution exhibited increases as the flow rate at feed solution inlet increased from 100 $mL \cdot min^{-1}$ to 300 $mL \cdot min^{-1}$, but then exhibited decreases when the flow rate at feed solution inlet further increased from 300 $mL \cdot min^{-1}$ to 650 $mL \cdot min^{-1}$. However, the overall loss of draw solute was determined to remain stable within the studied range of inlet flow rate.

In conclusion, experimental results suggested that to ensure the highest efficiency of water production, the flow rate at feed solution inlet of forward osmosis desalination systems need to be around 200 $mL \cdot min^{-1}$. However, it should also be noted that the flow regime of the fluids depends significantly on their viscosity and the characteristics of the vessels through which the liquid flows. Therefore, these experimental observations were realistically only valid for the specific experimental setups described in this study. In other circumstances, these results should only be used for reference, and detailed surveys should be implemented in order to optimize the performance of specific systems.

3.3. Influence of Relative Flow Direction

Experiments were conducted under two basic flow scenarios: co-current flow, and counter-current flow. In short, experimental results (as shown in **Figure 3**) indicated that water flux was higher in the counter-current flow scenario compared to the co-current flow scenario.

This result can be explained by the fact that in co-current conditions, the difference in natural osmotic pressure between the draw solution and the feed solution was greatest at the area around the two inlets, then gradually decreased towards the area around the two outlets. Conversely, in counter-current conditions, the difference in natural osmotic pressure between the draw solution and the feed solution remained relatively stable along the length of the semipermeable membrane. Generally, maintaining a stable difference in natural osmotic pressure between the draw solution and the feed solution is more beneficial as it helps alleviating various phenomena that can hinder the forward osmotic process, such as local concentration polarization or sudden decreases in osmotic driving force due to the natural resistance of the semipermeable membrane [10].

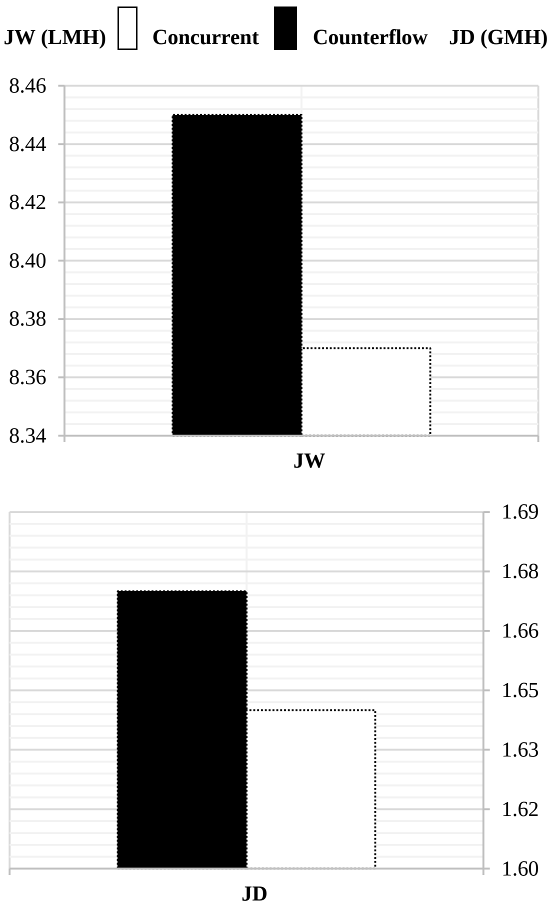

Figure 3 Influence of relative flow direction on water flux (JW) and reverse solute flux (JD)

3.4. Influence of Inlet Temperature

Experiments were conducted with the temperature at both feed solution inlet and draw solution inlet ranging from 10 °C to 40 °C, stimulatingly. Experimental results (as shown in **Figure 4**) indicated that inlet temperature can significantly influence the operational efficiency of forward osmosis desalination systems. Specifically, as inlet temperature increased from 10°C to 30°C, both water flux and reverse solute flux also increased, resulting in nearly unchanged overall draw solute loss. However, as inlet temperature continued to rise from 30 °C to 40 °C, water flux began to decrease from 8.51 to 7.32 LMH, while reverse solute flux remained increasing from 1.67 to 1.86 GMH.

This phenomenon can be explained by the fact that changes in temperature would lead to changes in characteristics of both the draw solution and the feed solution, specially their natural osmotic pressure and their viscosity, as well as affecting permeability properties of the semi-permeable membrane. Overall, experimental results from this study were quite consistent with several other previously published research focusing on the relationship between inlet temperature and water flux in forward osmosis systems [11,12].

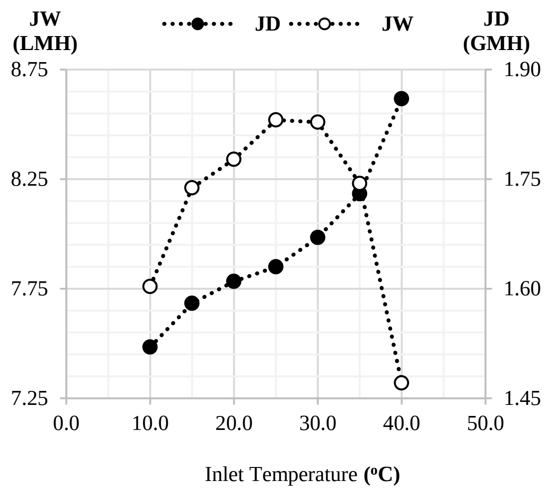

Figure 4 Influence of inlet temperature on water flux (JW) and reverse solute flux (JD)

Interestingly, experimental results from this study also showed some notable derivatives compared to other previously published research, which was the decline in water flux as inlet temperature increases from 30 °C to 40 °C. Since no derivative in reverse solute flux behavior was observed, the cause of this phenomenon could be due to temperature-dependent changes in semipermeable membrane properties. Specifically, as inlet temperature rises, compatibility between the semipermeable membrane and water may decrease, hindering the mass transfer of water through the membrane. This result underscores the importance of thoroughly investigating related properties of the semipermeable membrane in order to ensure the highest water production efficiency when operating a forward osmosis desalination system.

In general, the optimal inlet temperature determined within the scope of this study was around 25 °C to 30 °C. Notably, such temperature range is also commonly observed in many regions of Vietnam, demonstrating the suitability of the investigated draw solute and the selected semipermeable membrane for domestic desalination and freshwater production applications.

4. CONCLUSIONS

This study successfully established the relationship between the performance of forward osmosis desalination systems and several operational parameters.

In particular, water flux would increase with higher hydraulic pressure on the feed solution side, while reverse solute flux would increase with higher hydraulic pressure on the draw solution side. The influences of inlet flow rate and inlet temperature on operational characteristics of the forward osmosis system in this study were generally comparable to those reported in other published research, which showcased certain dependencies of forward osmosis performance on inlet flow rate and inlet temperature. However, in contrast to theoretical expectations, water flux was observed to reduce when temperature increased from 30 °C to 40 °C, which was likely due to temperature-dependent changes in properties of the semipermeable membrane. Conversely, changes in relative flow direction between feed solution and draw solution did not significantly affect observed water production efficiency of the forward osmosis desalination system in this study, which likely caused by the limitations in dimensions of the semipermeable membrane.

Within the scope of this study, optimal operational parameters for the highest efficiency of water production were determined, which include: hydraulic pressure difference to be 0.2 bar on the feed solution side, inlet flow rate to be around 200 $mL \cdot min^{-1}$, inlet temperature to be around 30 °C, and relative flow direction to be counter current. Under such conditions, the value for water flux achieved could reach 8.51 $L \cdot m^{-2} \cdot h^{-1}$, while the value for draw solute was only 1.67 $g \cdot m^{-2} \cdot h^{-1}$.

Overall, experimental results from this study provided a necessary theoretical foundation regarding the influence of various operational parameters on the performance of forward osmosis desalination systems using Polyvinylpyrrolidone K17 as a draw solute. Additionally, this study also emphasized the importance of thoroughly investigating related properties of the semipermeable membrane in order to ensure the highest efficiency when operating forward osmosis desalination systems.

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