

Optimization of the Utilization of Vacuum Membrane Distillations Lithium Bromida-Water Absorption Refrigeration System Using Response Surface Methodology

Bayu Rudiyanto, Tsair-Wang Chung, Armansyah H. Tambunan

Abstract — Response surface methodology (RSM) has been applied for modeling and optimization in utilization of vacuum membrane distillation on Lithium Bromide-water absorption refrigeration system (ARS). The effect of the operational parameter is initial feed concentration, feed inlet temperature, feed flow rate and interaction on the permeate flux. The developed model has been statistically validated by analysis of variance (ANOVA) and further used to predict the permeate flux. The results for the given factors is a saddle point one, which meant for the range given, there is no optimal value. This saddle point parameter is outside the data range which is concentration of 45.339 %, feed temperature at 62.934°C and flow rate 1.476 L.min⁻¹ while its predicted flux value is 100.392 g.m⁻².s⁻¹.

Keywords: Response surface methodology; lithium bromide-water; vacuum membrane distillation, optimization.

1 INTRODUCTION

Absorption cooling system was developed in 1850s by Ferdinand Care and became the primary cooling system at that time before the invention of vapor compression refrigeration machine in 1880. As a power resource, absorption refrigeration system uses thermal energy to produce cooling cycle mechanism not compressor which used in vapor compression refrigeration system. The effect is *Coefficient of Performance* (COP) product is lower but the system has several advantages i.e. provide more secure environmental effects. It also requires lower energy consumption compared with the other [1], [2]. There are several heat energy resources such as energy exhaust from machinery or plant, solar energy, geothermal energy and energy produced from agricultural waste [3]. But not all temperature generated is able for regeneration process in cooling mechanism.

Regeneration is one of the main processes in the mechanism where generator absorbs heat to separate water from the solution of LiBr-H₂O in high temperature. This requirement of high temperature is the constraint on separation process. [1] stated that generator on absorption system using LiBr-H₂O which operates at below 80°C will produce low COP. Meanwhile, according to [4], the use of generator in lithium bromide absorption refrigeration system which operates at 80-93°C will produce average COP at 0.725. Increasing COP number was also conducted by [4] by adding steam compressor which placed between generator and condensor. Steam compressor reduced vapor pressure when temperature getting lower and resulted COP at 0.65-0.75. Based on several studies above, it is necessary to develop alternative processes to improve high temperature requirement in generator to separate LiBr-H₂O solution. Moreover, the large contact area was needed to separate water vapor from aqueous lithium bromide solution which makes

traditional generator bulky and heavy to be fitted into small scale device [6].

The membrane distillation (MD) is a process for vapor extraction from aqueous solution at temperature which may be much lower than the boiling point of the solution [7-12]. Vacuum membrane distillation (VMD) is another variant of MD. In this configuration low pressure or vacuum is applied on the permeate side of the membrane module by means of vacuum pumps [13-16]. The applied permeate pressure is lower than the saturation pressure of volatile molecules to be separated from the feed solution and condensation takes place outside the membrane module at temperatures much lower than the ambient temperature. The development of membranes used in the absorption cooling system still focuses on the selection of membrane types. [3] performed separation of LiBr-H₂O solution using vacuum membrane distillation with *polyvinylidene fluoride* (PVDF) to overcome the requirement of high regeneration temperature which resulted in lower temperature up to 67°C.

Using VMD in absorption refrigeration system ARS will cause several problems, including the achievement of optimal conditions to operate. The influential parameter in this process which were temperature, pressure, flow rate and concentration of the solution. Thus, to identify the optimal parameter VMD application on absorption refrigeration system, it is necessary to use statistical study. The purpose of this study was to determine the important parameters in the process of separation-aqueous LiBr.

2 EXPERIMENTAL SET UP

The experimental device was showed in Fig 1. The central part is a commercial shell-and-lumen membrane module UMP-0047R, supplied by Mycroza is trademark of Asahi Kasei Corporation. Basically, it consists of a set of equal *polyvinylidene fluoride* (PVDF) porous hydrophobic capillaries, assembled and made into a shell-and-lumen module. Hot feed of aqueous lithium bromide solution flows into the lumen side while the shell chamber is keeping in a vacuum state by cooling water or by vacuum pump. Fig 2 (a and b), shows the hollow fiber membrane module, in which twenty one of PVDF capillaries are assembled in plastic body and sealed securely to both ends. The principal characteristics of the hollow fiber membrane, as specified by the manufacturer, are showed in Table 1 and Table 2.

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TABLE 1
SPECIFICATION MATERIAL CONSTRUCTIONS OF
MEMBRANE MODULE

Specifications material constructions :	
Membrane	: Polyvinylidene fluoride (PVDF)
Housing	: Native clear polysulfone (P) or filled polysulfone (W)
Potting Material	: Epoxy Resin
Gasket	: Silicon (P)
Bacteriostat	: Glycerin 65%, Ethanol 2 %, Water balance

TABLE 2
PART NUMBER AND TECHNICAL SPECIFICATION OF THE MEMBRAN MODULE

Part Number and Technical Specification :	
Part Number	: UMP-0047R
Number of membrane	: 21
Fiber ID/OD (mm)	: 1.4/2.2
Nominal Length(mm)	: 310
Membrane Area (m ²)	: 0.02
Clean Water Flux (Lh ⁻¹ bar, 25°C)	: 19
Crossflow Rate for 1 ms ⁻¹ Fluid velocity	: 116
Maximum Pressure (barg)	: 3/3/1.5
Feed/TMP/Permeate at 50°C	
Volume Feed	: 23
Volume Permeate (mL)	: 30

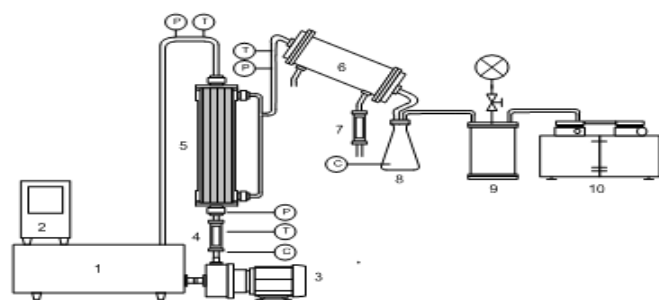


Fig. 1. Experimental VMD set-up: 1. water bath; 2. thermostat water bath; 3. Pump; 4. solution flowmeter; 5. VMD module; 6. Condenser; 7. Cooling water flowmeter; 8. Receiving tank; 9. Cold trap; 10 Vacuum pump



Fig 2. PVDF hollow fiber membrane module used in this research

The temperature and pressure of the liquid feed were measured at the inlet and outlet of the membrane module. The temperature and pressure were measured continuously, in steady state. The temperature of the hot feed was measured at the inlet and outlet of the membrane module, while the temperature of water vapor was measured at the outlet of the permeation side. The temperatures was measured with thermocouple which connected to a digital multi-meter, with an accuracy ± 0.1 °C and the pressure was measured with pressure control type GP-D-0040GAPX, with an accuracy of 0.001 bar. The feed inlet temperature was controlled by a thermostat Water Bath G-20 DENG YNG, with a temperature fluctuation of less than ± 0.1 °C.

The liquid feed was circulated with a circulation pump FLOJET MOD: 2130-546-115 and the feed flow was measured with a flowmeter HJ-981204-25D-S, with precision $\pm 2\%$. The volume of solution in water bath was determined in the beginning of experiment.

A water circulating vacuum pump GAST Model DAA-V503-EB) with a pressure adjuster was connected to the permeation side of the membrane module to produce the vacuum condition before the test began, and then the vacuum pressure would maintain constant at the condensing temperature of cooling water during the test. A glass cold trap by cooling water was connected to the permeation side to recover the water vapor.

The flux of distilled water was calculated, in every case, by measuring of the permeate flux every ten minutes, during two hours, and by measuring the concentration before and after the process of using refractometer index (RI). Permeation flux means the quality of permeation water per unit area in an hour. The permeation flux is described as followed :

$$J = \frac{W}{(S.t)} \quad (1)$$

Where J is the permeation flux, (kg.m²h⁻¹); W is the quantity of water, kg; S is the membrane area, m²; and t is the time, h.

The operating parameter region of solution concentration, temperature and flow rate was showed in Table 3. Volume of the aqueous lithium bromide solution used in the experiment was 5 liter, but effective internal membrane area of hollow fiber module was only 0.02 m². Table 3 shows the operating region and the levels of the variables in actual and coded values. The measured VMD distillate fluxes, the responses and the standard deviations are also presented in table 4. The experimental design and analysis of data were done by using a commercial statistical package, JMP software version 7. By using the software, a Box-Behnken design with 3 center points was employed with three factors and three levels. This design is not randomized. The Box-Behnken design contains of 15 experiments with three center points.

TABLE 3
CODED AND ACTUAL DESIGNED VARIABLES USED
FOR THE EXPERIMENTAL DESIGN

Design variables (factor)	Coded Variables	Actual values of coded levels		
		-1	0	+1
Concentration (%)	x_1	45	47.5	50
Temperature (°C)	x_2	60	70	80
Flow rate (L/min)	x_3	1.1	1.5	1.9

3 RESULT AND DISCUSSION

The response surface model (RS-model) with interaction terms was developed for the VMD distillate flux using eq 2 and the experimental data was summarized in the table 4.

$$y = b_0 + \sum_{i=1}^n b_i x_i + \sum_{i=1}^n b_{ii} x_i^2 + \sum_{i < j}^n b_{ij} x_i x_j \quad (2)$$

Where y is the predicted response, x_i is the coded variables, and b_0 , b_i , b_{ii} , b_{ij} are the regression coefficient. The values of the regression coefficients were determined using the ordinary least square method written as follows [17]:

$$b = (x'x)^{-1} x'y \quad (3)$$

Where b is a column vector of the regression coefficients, x is the design matrix of the coded levelsof the input variables and y is column vector of the response.

TABLE 4

BOX-BEHNKEN DESIGN AND EXPERIMENTAL VMD							
No. Run	Factor (Controllable input variable)						Response J_w (kg m ⁻² s ⁻¹).10 ⁻³
	Concentration (%)		Temperature (°C)		Flow rate (L.min ⁻¹)		
	x_1	C	x_2	T	x_3	m	
1	0	47.5	-	60	+	1.9	87.005
2	+	50	-	60	0	1.5	35.293
3	+	50	+	80	0	1.5	344.390
4	0	47.5	-	60	-	1.1	298.482
5	-	45	0	70	+	1.9	410.005
6	-	45	-	60	0	1.5	151.973
7	-	45	0	70	-	1.1	124.323
8	0	47.5	0	70	0	1.5	158.798
9	-	45	+	80	0	1.5	777.363
10	+	50	0	70	-	1.1	150.855
11	0	47.5	0	70	0	1.5	141.078
12	0	47.5	0	70	0	1.5	127.403
13	0	47.5	+	80	+	1.9	930.068
14	+	50	0	70	+	1.9	120.593
15	0	47.5	-	80	-	1.1	418.938

The obtained RS-model is written in eq 4, as a function of the coded variables and permits to predict the distillate flux J_w (in kg/m².s), as follows:

$$Y = 142.426 + 101.567x_1 + 237.251x_2 + 69.384x_3 - 79.073x_1x_2 - 78.966x_1x_3 + 180.652x_2x_3 - 23.675x_1^2 + 208.504x_2^2 + 82.693x_3^2 \quad (4)$$

It should be pointed out that the RS-model includes only the significant term. The significance of the regression coefficients was given in eq 4. Fig 3, gives the plot of experimental and predicted value. Moreover, the statistical validation of the RS-model was performed by means of analysis of variance (ANOVA). The results were presented in Table 5.

TABLE 5
ANALYSIS OF VARIANCE (ANOVA) OF THE RSM
MODEL CORRESPONDING TO THE RESPONSE :
PERFORMANCE INDEX (Y)

Source	DF ¹	SS ²	MS ³	F Ratio	R ²	R ² _{adj}
Model	9	936253.56	104028	46.753	0.988	0.967
Error	5	11125.24	2225			
C.	14	947378.81				
Total						

¹ Degree of freedom

² Sum of squares

³ Mean of square

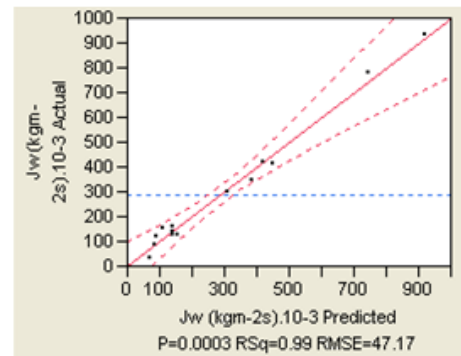


Fig3. Comparison between the experimental and predicted VMD performance index (Y) determined by the RSM model.

The mathematical equation used to calculate the ANOVA estimators (i.e. SS, MS, F-value, R², R²_{adj}) are detailed elsewhere. As can be seen in Table 5, the F-value is high, P- value smaller than 0.0003 and R² value is about 0.988 in agreement with the adjusted coefficient of determination R²_{adj}. These indicate that the RS-model eq 4, is statically valid and can be used for prediction of the VMD distillate flux.

The significance of the regression coefficient of the models written as function of the coded variables could be tested with statistical Student t -test. Table 6 shows the t - test result for the experiment. From the test results, it shows that the feed initial temperature (x_2), concentration (x_1) and flow rate (x_3) are significance. Furthermore, its interaction effect with the feed initial concentration and temperature, concentration and feed flow, temperature and feed flow are still significant.

TABLE 6
PARAMETER ESTIMATES AND t -TEST RESULT

Term	Estimate	Std Error	t Ratio	Prob> t
x_2 (°C)	237.25062	16.67726	14.23	<0.0001*
x_2 (°C)* x_1 (°C)	208.50396	24.54826	8.49	0.0004*
x_2 (°C)* x_3 (L/min)	180.65175	23.58521	7.66	0.0006*
x_1 (%)(45,50)	-101.5665	16.67726	-6.09	0.0017*
x_1 (L/min)(1.1,1.9)	69.384125	16.67726	4.16	0.0088*
x_3 (L/min)*	82.693208	24.54826	3.37	0.0199*
x_3 (L/min)				
x_1 (%)* x_2 (°C)	-79.07325	23.58521	-3.35	0.0203*
x_1 (%)* x_3 (L/min)	-78.98625	23.58521	-3.35	0.0204*
x_2 (%)* x_1 (%)	-23.67529	24.54826	-0.96	0.3791

The response surface for the given factors and response is a saddle point one, which meant for the range given, there is no optimal value. This saddle point parameter is outside the data range which set is concentration of

45.339 %, feed temperature at 62.934°C and flow rate 1.476 L.min⁻¹ while its predicted value is 100.392 g.m⁻².s⁻¹.

To have a more understanding on the effect of each parameter and their interaction, a prediction profiler of the experiment is shown at Fig 4. As can be seen, the feed inlet temperature shows an obvious increasing curvature since its significance. The initial feed concentration shows a slight decreasing curvature which shows its effect on the response. The feed flow shows a slight increasing curvature which shows its effect on the response.

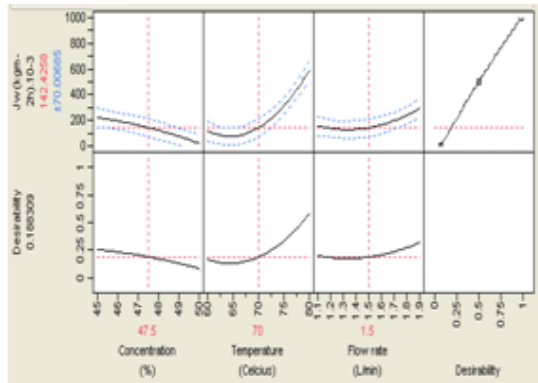


Fig 4 Prediction profiler of experiment result

The effect of the VMD operating parameters on the distillate flux are plotted in Fig 5-7 in 3-D and 2-D contour plots. For example, Fig 5, shows the effect of the feed inlet temperature (x_2) and initial feed concentration (x_1) on the permeate flux. As can be seen, the increase of initial feed concentration will lead to a decrease of the permeate flux while the increment of feed inlet temperature will lead to an increase of the response. At high concentration, the effect of temperature is stronger than at low concentration. For example, at concentration between 45%-50%, at temperature of 60°C and feed flow 1.5 L.min⁻¹ will produce permeate flux from 112.497 g.m⁻².s⁻¹ to 67.511 g.m⁻².s⁻¹. In contrast, at concentration 45 % and temperature between 60°C-80°C will produce permeate flux from 112.497 g.m⁻².s⁻¹ to 739.764 g.m⁻².s⁻¹. The graph also confirms the strong effect of the feed inlet temperature over the initial feed concentration.

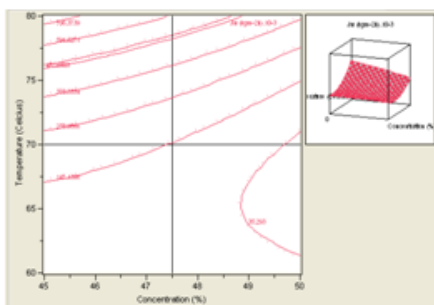


Fig 5 Response surface plot and contour profiler showing the VMD performance index (Y) as a function of Temperature (°C) and Concentration (%) for flow rate 1.5 (L.min⁻¹)

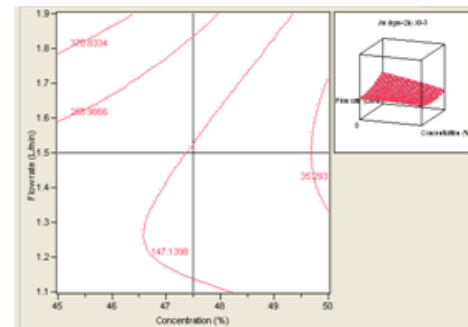


Fig 6 Response surface plot and contour profiler showing the VMD performance index (Y) as a function of flow rate (L.min⁻¹) and Concentration (%) for temperature 70 (°C).

Fig 6, shows the effect of flow rate (x_3) (L.min⁻¹) and concentration (x_1) (%) on the response Y. The main effect of flow rate (x_3) (L.min⁻¹) is greater than the main effect of concentration (x_1) %. The increase of both variable leads to the enhancement of Y. As it is mentioned before, due to the quadratic effect of x_1 , the response Y increases up to a maximum and then decreases for high x_1 values. Interaction effect x_3 and x_1 on the response Y is significant, although these interactions give negative values.

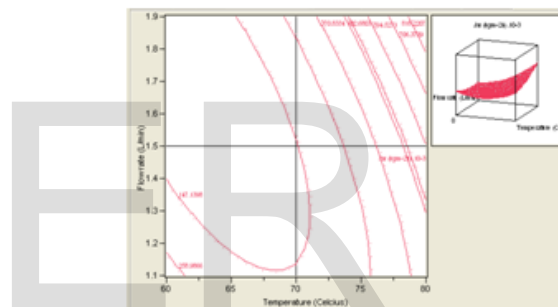


Fig 7 Response surface plot and contour profiler showing the VMD performance index (Y) as a function of flow rate (L.min⁻¹) and temperature (°C) for concentration 47.5 (%).

Fig 7, shows a strong main effect of temperature (x_2) (°C) on the response Y. The increment of this variable conducts to an increase of Y and the main effect of flow rate (x_3) (L.min⁻¹) is smaller compared to the main effect of temperature. However, the quadratic effect of x_2 is greater than the quadratic effect of x_3 , and the interaction effect between temperature and flow rate is significant and gives a positive value.

4 CONCLUSIONS

Design of experiments and response surface methodology (RSM) were applied for desalination by VMD. According to the predictions of the performance index the highest positive effect was attributed to the feed inlet temperature. The feed flow rate had small positive and the concentration had negative effect, i.e. the increase of this factor led to a gradual reduction of the permeate flux. All factors have quadratic effects and a small interaction effect on the specific performance index was detected between concentration versus flow rate, and concentration versus temperature.

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Nomenclature

DF	degree of freedom
F-value	ratio of variances (ANOVA test)
i and j	subscripts (integer variables)
J_w	permeate flux
MS	mean square (ANOVA test)
P-value	probability in statistical significance testing (ANOVA test)
R^2	coefficient of multiple determination
R^2_{adj}	adjusted statistic coefficient
SS	sum of squares (ANOVA test)
x1, x2, x3	coded levels of variables (factors)
Y	performance index
*	superscript indicating optimal values of variables

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