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# A study on criteria of the evaluation method of MBR membrane replacement

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**Abstract:** All 3520 days permeate volume and trans-membrane pressure of an $A^2$/O-MBR RWTP in Xi'an Siyuan University have been indiscriminately used to study an evaluation method of MBR hollow fiber membrane replacement. The industrial permeability, VMD, has been defined as a fraction with the numerator of permeate volume and the denominator of trans-membrane pressure, $m^3$/ (1000-$m^2$.day.kPa), without temperature normalization. Based on our practical operation, as membranes age, three phenomena can be observed simultaneously. The VMD is decreased 0.78 $m^3$/ (1000-$m^2$.day.kPa), about 4.28% annually; The TMP is increased 0.66 kPa, about 3.50% annually, and the present production capacity is decreased 47 $m^3$ per day, about 2.47% annually; The frequency of cleaning events is increased. In a practical point of view, the membrane replacement interval is a technical and economic planned exercise. Even though, data used in this paper have come out with limitation, but the methodology used still be meaningful.

**Keywords:** membrane bioreactor; membrane replacement; industrial permeability ; trans-membrane pressure; annual permeability attenuation.

**Abbreviation:** MBR, membrane bio-reactor; PPC, present production capacity, $m^3$/day; RWTP, reclaimed water treatment plant; TMP, trans-membrane pressure; TMP1, arithmetic mean of group TMP; TMP2, arithmetic mean of annual TMP; VMD, industrial permeability, $m^3$/ (1000-$m^2$.day.kPa); VMD1, arithmetic mean of group VMD; VMD2, arithmetic mean of annual VMD.

## I. INTRODUCTION

The critical issue of the latest cutting-edge eco-technologies for a sustainable transition in wastewater treatment is to be profitable. In other words, it is to make money, at least to break even, or the treated water can be reused, and its revenue, without calculating taxes and return on investment, can be balanced with the capital cost and operation cost. If the revenue never balances operating costs, management fees, and the depreciation of the project capital cost, then these technologies can reach the market only through government finance. The pursuit of using multi-channel, multi-subject, and multi-mode market economy, such as social funds, private money, and public resources, to achieve the market-oriented operation of urban sewage treatment infrastructure construction is impossible. To be profitable of a bio-membrane reactor wastewater treatment plant, one of the special attentions should be given to the membrane replacement. China has operated its first industrial scale MBR in 2006[1]. Many relevant areas of MBR, such as application engineering design [2-5], membrane fouling and cleaning prevention [6-8], and cost analysis etc. [9-11] have been studied and results have been transferred into practice. But only few papers are related to membrane replacement evaluation [12-15]. At present, there are more qualitative descriptions of membrane life, such as "the time for which the membrane or membrane element maintains the predetermined performance under normal conditions of use" [16], or "when the running time of the membrane reaches a specified service life or causes damage during use, chemical cleaning cannot restore its function" [17]. The judgment of each membrane manufacturer on the life of the membrane is usually based on the water production of the membrane system or the quality of the water production cannot meet the user's requirements. There are also two quantitative descriptions of membrane life. The first is "under the design and operation conditions, the service life of the membrane element is not less than 3 years" [18]. It is feasible to use the permeability decay curve to reflect the irreversible fouling of the membrane qualitatively. Therefore, the accuracy and details of those predictions cannot be found. An $A^2$/O-MBR (Anaerobic- Anoxic-Aerobic Membrane Bioreactor) RWTP has been built in 2011 and started to operation in Xi'an Siyuan University [19-23]. This aging RWTP has been still running without replacing any membrane, which offers new insights from an operational perspective. Several issues can in fact be disclosed only after such long-term operations in sub-optimal conditions, such as the designed flow diagram effects, inter-relation between constant flux operation and membrane cleaning procedures, etc. This paper takes MBR near 10 years operation of as an example, from the rationality and practicability point of view, quantitatively focus on the MBR membrane replacement.

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## II. XIAN SIYUAN UNIVERSITY $A^2$/O-MBR RWTP

A. The flow diagram of $A^2$/O-MBR of Xi'an Siyuan University RWTP

Xi'an Siyuan University uses PVDF hollow fiber membrane for an $A^2$/O-MBR membrane RWTP with the production capacity of 2000 $m^3$/d and operated in constant flux mode with designed flux LMH=16.0. The designed production capacity (DPC) for each membrane tank is

$$\frac{16L}{1hour.m^2}\frac{1800m^2}{1tank}\frac{1m^3}{1000L} = 28.8\frac{m^3}{tank.hour} \quad (1)$$

So, the DPC of 24 hours for RWTP, 1#, 2#, and 3# membrane tanks, is 2000$m^3$. Each membrane tank has its own permeate pump to avoid the uneven flow distribution and rapid fouling of membranes. Figure 1 shows the current process flow of the $A^2$/O-MBR reclaimed water plant.

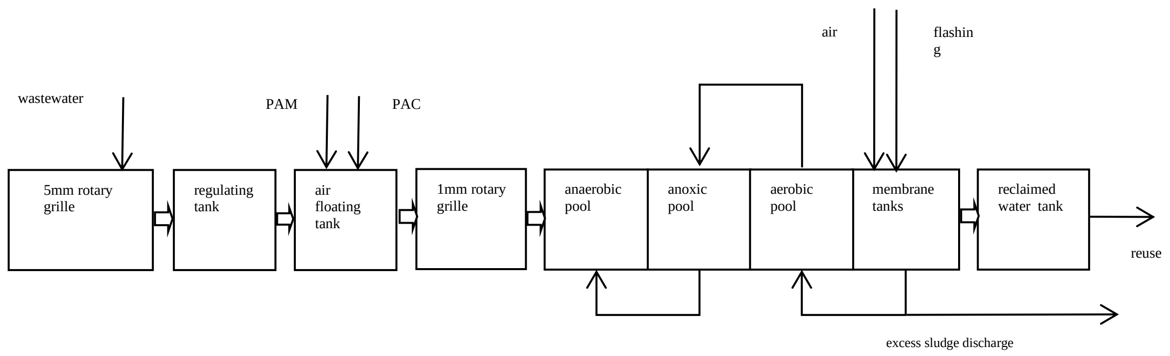


**Figure 1.** The flow diagram of $A^2$/O-MBR of Xi'an Siyuan University RWTP

B. Time frame for the membrane operation data collecting

From 31st October 2011 to 31st October 2021, a total of 3,651 days of running data of 1#, 2#, and 3# membrane tanks, is selected for the membrane permeability study. The RWTP is closed from January 8 to May 19 in 2020 for 131 days. The actual number of days in this study are 3520 days, 9.644 years.

C. Maintenance and cleaning of membrane

MBR was pumped intermittently pumped by a self-suction pump with a stop time ratio of 9 min/1.0 min. During the MBR operation, the membrane trapped the solid suspension in the mixture, and formed a compressible filter cake on the membrane surface which needs to be controlled to ensure that the TMP remains within a reasonable range during the filtration process. To effectively control the membrane pollution and cake layer, extend the service life of the membrane, four kinds of membrane cleaning, Membrane Back Wash (performed automatically by a self-suction pump), Maintenance Cleaning (EFM), Chemical Offline Cleaning (CIP), and Physical cleaning, have been carried out since the MBR starts running.

## III. PERMEABILITY ATTENUATION

A. Industrial permeability (VMD)

All pieces of data include the daily water inlet flow, TMP, suction pump frequency, turbidity, pH value, temperature, reclaimed water yield, etc. for over 10 years are available. This provides us a unique position to analyze the permeability attenuation phenomena and answer some operational questions. Industrial permeability (VMD) has been defined as a fraction with the numerator of permeate volume and the denominator of trans-membrane pressure, $m^3$/(1000-$m^2$.day.kPa), without temperature normalization.

B. Valid industrial permeability

There are a few kinds of abnormalities in the 3520 daily VMD, such as both numerator and denominator were zero, one of numerator and denominator was zero or very small. Those abnormalities were caused by the objective reasons, such as instrument malfunction or fixed recording time, etc. After removing all the abnormal points one by one, the "valid industrial permeability" of each membrane tank is produced. The number of valid VMD for the three membrane tanks are listed in Table 1. Figure 1 to Figure 3 represent the valid VMD value vs time for three membrane tanks.

 

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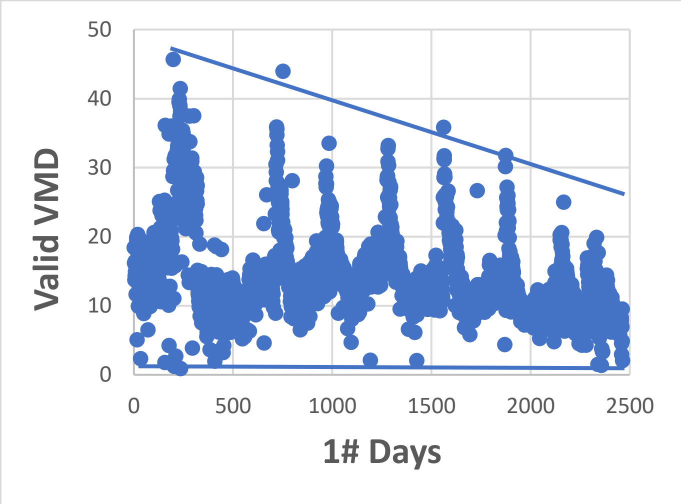


Figure 1: VMD value vs time of 1# membrane tank

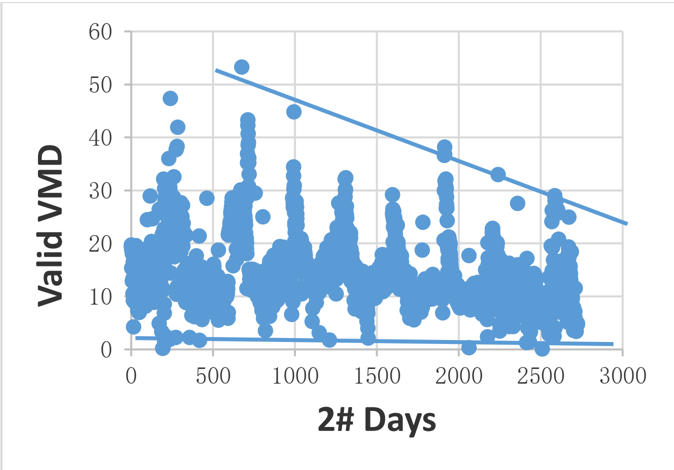


Figure 2: VMD value vs time of 2# membrane tank

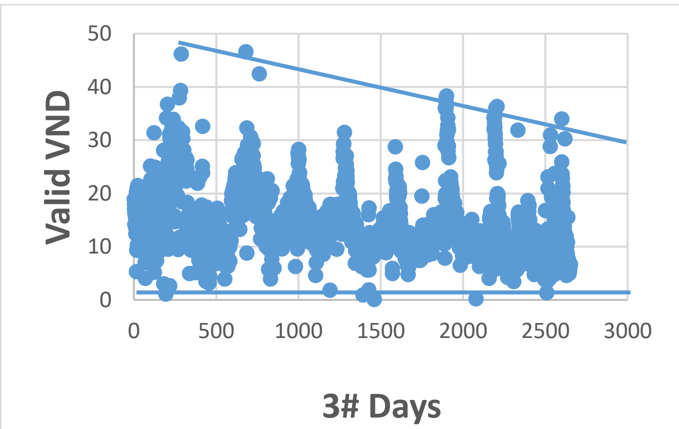


Figure 3: VMD value vs time of 3# membrane tank

It is easy to observe the VMD value is generally decrease with the running time. In the actual operating condition, VMD value is declining, and up-down distribution is narrowed along with time. Obviously, two lines can be drowned in the each of Figure 1-3: one upper end line places along the highest points, and another lower line draws following the lowest points. Since the industrial permeability (VMD) has been defined as a fraction with the numerator of permeate volume and the denominator of trans-membrane pressure, there are three ways can cause VMD decreasing, such as

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decreasing the numerator, increasing the denominator, or decreasing the numerator and increasing the denominator simultaneously. For over 10 years data quantitatively analysis, the attenuation of industrial permeability (VMD) has been caused by decreasing the numerator and increasing the denominator simultaneously. For quantitatively calculating the attenuation of industrial permeability, two dimensionality reduction of the over 10 years data must be done.

C. The first dimensionality reduction and statistical calculation

Since there are over twenty-five hundreds of valid VMD for each membrane tank, the first dimensionality reduction is conducted by artificially grouping 25 valid daily VMD into one group.

The VMD1 is the arithmetic mean within each group, and is calculated by:

$$VMD1 = \frac{\sum_{i=1}^{25} x_i}{25} \qquad (2)$$

Where $x_i$ is the $i^{th}$ VMD, and there are 25 valid VMD in one group unit. There are three membrane tanks in Xi'an Siyuan University RWTP.

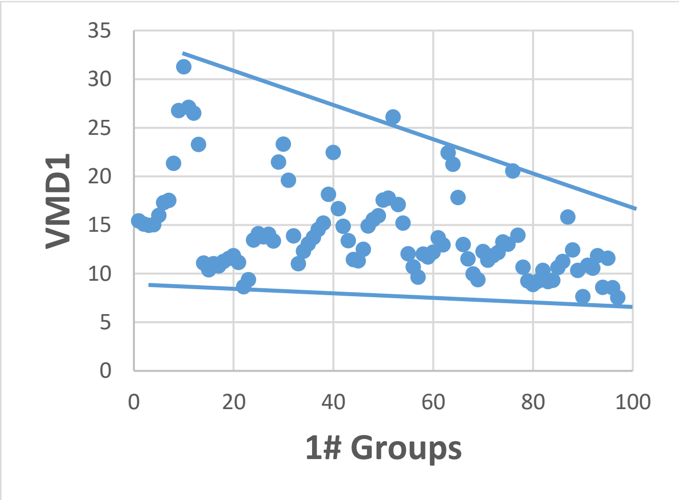


Figure 4: The VMD1 vs time of $1^{\#}$ membrane tank

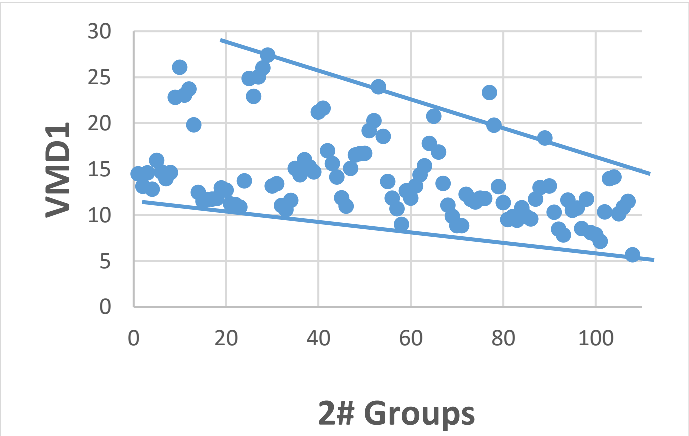


Figure 5: The VMD1 vs time of $2^{\#}$ membrane tank

  

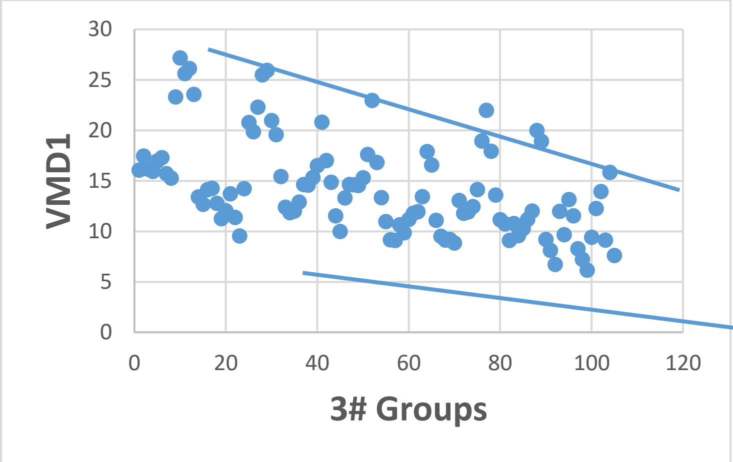


Figure 6: The VMD1 vs time of $3^{\#}$ membrane tank

The first dimensionality reduction results of all three tanks are listed in Table 1.

Like the VMD value and the running time, the VMD1 value is similarly decreased with the running time. This similarity between VMD and VMD1 proves the first dimensionality reduction does not lose the characteristic of attenuation. Obviously, two lines can be drowned in the each of Figure 4-6: one upper end line places along the highest points, and another lower line draws following the lowest points.

D. The second dimensionality reduction and statistical calculation

The group units of each membrane tank have a specific time relationship with the number of operating years. As the data in Table 1 show that there are 98 VMD1 values for the 98 VMD groups in the $1^{\#}$ membrane tank. The running time represented by the 98 VMD groups is 9.644 years, and the 98/9.644=10.16 groups are equal to 1 year. While for the $2^{\#}$ membrane tank the 109/9.644=11.30 groups are equal to 1 year. While for the $3^{\#}$ membrane tank, the 106/9.644=10.99 groups are equal to 1 year. The specific time relationship between the number of groups to one operating year is defined as the "ratio". The ratio of VMD1 for three membrane tanks is listed in Table 1.

TABLE 1: VMD FOR EACH OF THE THREE MEMBRANE TANKS

| Item | $1^{\#}$ | $2^{\#}$ | $3^{\#}$ |
|---|---|---|---|
| VMD/day | 3520 | 3520 | 3520 |
| valid VMD/day | 2474 | 2725 | 2652 |
| Group/# | 98 | 109 | 106 |
| Time/year | 9.644 | 9.644 | 9.644 |
| Ratio/#/year | 10.16 | 11.30 | 10.99 |

The second dimensionality reduction of VMD is annually conducted and resulted VMD2.

The VMD2 is calculated based on:

$$VMD2 = \frac{\sum_{i}^{j} x_i}{j-i} \tag{3}$$

Where $x_i$ is the $i^{th}$ VMD1, and there are i to j groups VMD1 in the calculation. The regular VMD2 values of the $1^{\#}$ membrane tank are listed in Table 2.

TABLE 2: VMD2 OF THE $1^{\#}$ MEMBRANE TANK

| Year | VMD2 | i to j /# | Year | VMD2 | i to j /# |
|---|---|---|---|---|---|
| 1 | 19.071 | 1-10 | 6 | 14.781 | 52-61 |
| 2 | 15.486 | 11-20 | 7 | 14.513 | 62-71 |
| 3 | 14.276 | 21-30 | 8 | 12.501 | 72-81 |
| 4 | 15.398 | 31-40 | 9 | 10.712 | 82-91 |
| 5 | 14.422 | 41-51 | 9.644 | 9.944 | 92-98 |

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The VMD2 of other two membrane tanks can be calculated through the same method with different i to j values. Instead of treating each individual tank VMD2 separately, furthermore, three tanks' VMD2 can be treated as "three in one" together, as shown in Figure 7.

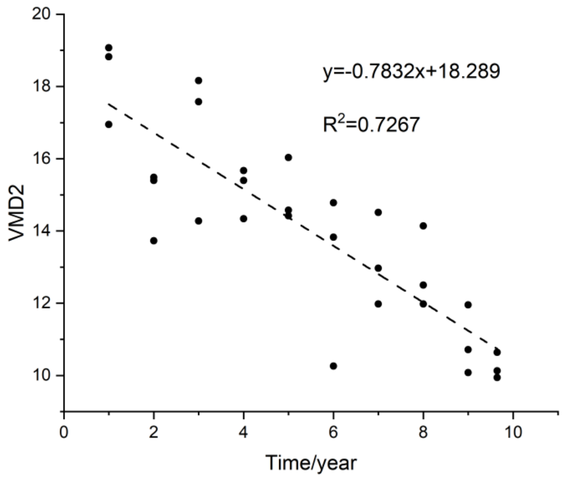


Figure 7: Three in one's VMD2 vs time

Clearly, the correlation between VMD2 and time is a linear relationship, can be presented mathematically with gradient intercept form as

$$y = ax + b \tag{4}$$

Where a is the slop and b is the intercept.
Three individual membrane tanks and "three in one" VMD2 vs time equation parameters are listed in Table 3.

TABLE 3: THE PARAMETERS OF MEMBRANE TANKS AND THREE IN ONE VMD2 vs TIME

| Membrane tank | a | b | $R^2$ |
|---|---|---|---|
| 1# | -0.7792 | 18.369 | 0.7985 |
| 2# | -0.7446 | 18.014 | 0.7304 |
| 3# | -0.8256 | 18.486 | 0.6746 |
| Three in one | -0.7832 | 18.289 | 0.7267 |

The characteristic in Table 3 is the negative slops, which is the incontestable evidence regarding the MBR membrane VMD2 attenuation. Based on three in one data, the VMD will decrease about 0.7832 $m^3$/ (1000-$m^2$.day.kPa) annually.
There are at least five merits regarding the method of permeability attenuation calculations.

1) It is very convenient to collect all original data, permeate volume per day and trans-membrane pressure, without temperature adjustment.
2) It is very easy to carry out three calculations, removing all the abnormal points one by one, conducting the first dimensionality reduction, and conducting the second dimensionality reduction.
3) From previous research articles, permeability declined evaluation is based on few data of the days before and after the offline chemical cleaning, 99% of daily data is abandoned and wasted. If only a few points, less than 1% has been used in the assessment, then the result is unconvincing. Using this method, every daily data has been indiscriminately used to study an evaluation method of MBR hollow fiber membrane attenuation.
4) It is well known that high temperature in summer season will benefit the permeate, and big rainfall can significantly reduce the effluent concentration and lead to increase the permeate. So, the daily permeability data needs the temperature adjustment to compare with each other. But if an annual average permeability data is used, those seasonal temperature and rainfall could not be the problem anymore. There will not be necessary to do the adjustment.
5) Not matter using net present value in bases for comparison of alternatives, or using depreciation in benefit-cost analysis, the most common time of economic assessment is year.

E. Trans-membrane pressure

The data of TMP should be treated follow the same procedure, collecting every daily TMP, eliminating unusual ones, grouping 25 valid TMP as the first dimensionality reduction, then, the second dimensionality reduction to get the annual TMP2. Each individual tank TMP2 can be treated separately, or, three tanks' TMP2 can be treated as "three in one" together, as shown in Figure 8.

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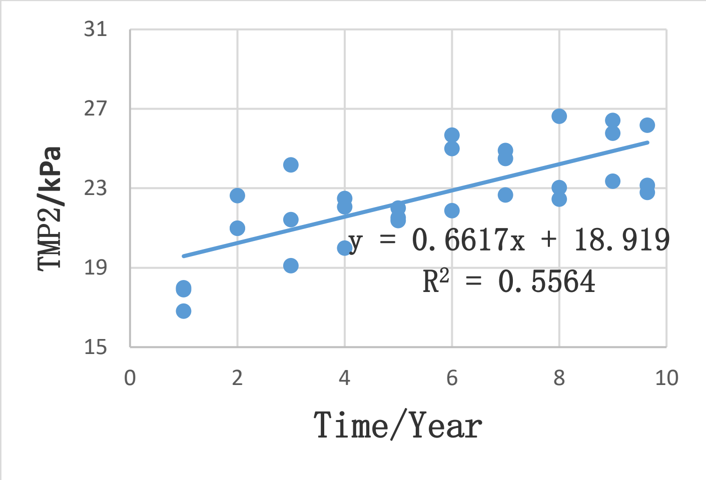


Figure 8: The linear relationship of TMP2 vs time for “three in one” All three-membrane tank’s TMP2 vs time equation parameters are listed in Table 4.

TABLE 4: THE PARAMETERS OF MEMBRANE TANKS AND THREE IN ONE TMP2 vs TIME

| Membrane tank | a | b | $R^2$ |
|---|---|---|---|
| 1# | 0.8363 | 19.165 | 0.6681 |
| 2# | 0.4766 | 19.005 | 0.7323 |
| 3# | 0.6723 | 18.587 | 0.6405 |
| Three in one | 0.6617 | 18.919 | 0.5564 |

The characteristic in Table 4 is the positive slops, which is the incontestable evidence of building-up of the trans-membrane pressure. Based on three in one data, the TMP will increase about 0.66 kPa annually.

F. Present production capacity（PPC）

Typically, as membranes age, its irreversible fouling aggravated. Three phenomena can be observed simultaneously: the industrial permeability quantitatively declined; the trans-membrane pressure quantitatively increased, and the frequency of cleaning events qualitatively increases. Based on the specific value VMD2 and TMP2 of each individual membrane tank or three in one, the present production capacity（PPC, $m^3$/day）can be calculated through:

$$PPC\,\frac{m^3}{day} = VMD2xTMP2x1.8 \qquad (5)$$

Based on data of three in one, the total PPC at different year is plotted in Figure 9.

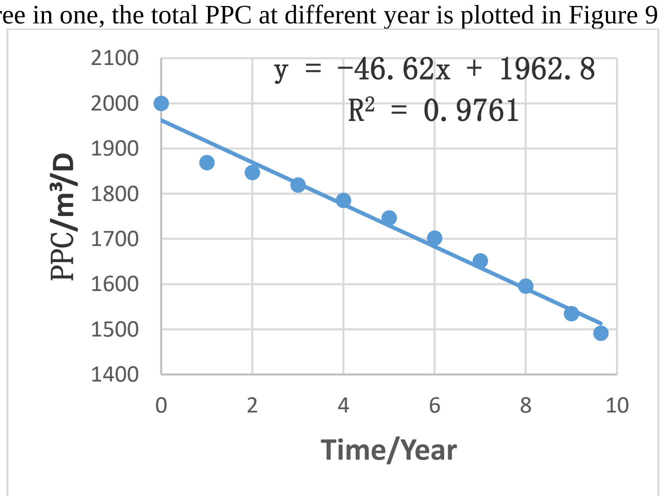


Figure 9: The linear relationship of PPC vs time for “three in one”

The present production capacity will annually decrease 47 $m^3$ per day. After nearly 10 years operation, present production capacity is about 1490 $m^3$ per day for RWTP, which is equal 74.5% of the original designed capacity of 2000 $m^3$ per day.

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## IV. CONCLUSION

All 3520 days permeate volume and trans-membrane pressure of an $A^2$/O-MBR RWTP in Xi'an Siyuan University have been indiscriminately used to study an evaluation method of MBR hollow fiber membrane replacement. The industrial permeability, VMD, has been defined as a fraction with the numerator of permeate volume and the denominator of trans-membrane pressure, $m^3$/ (1000-$m^2$.day.kPa), without temperature normalization.

Based on our practical operation, as membranes age, three phenomena can be observed simultaneously. The VMD is decreased 0.78 $m^3$/ (1000-$m^2$.day.kPa), about 4.28% annually. The TMP is increased 0.66 kPa, about 3.50% annually, and the present production capacity is decreased 47 $m^3$ per day, about 2.47% annually. The frequency of cleaning events qualitatively increases.

The membrane replacement is a technical and economic planned exercise. There are pro membrane replacement, such as lower TMP, lower energy cost, less chemical cleaning, higher chemical cleaning efficiency, lower operation cost, and lower potential risks in operation. The pro for continual running without membrane replacement is no new membrane purchasing cost, no capital cost, but the cons are higher TMP, higher energy cost, more chemical cleaning, lower chemical cleaning efficiency, higher operation cost, and higher potential risks in operation. The decision of planned exercise is to calculate whether earlier membrane replacement can be counterbalanced by pros and cons.

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## REFERENCES

[1] K. Xiao, Y. Xu, S. Liang, T. Lei, J.Y. Sun, X.H. Wen, H.X. Zhang, C.S. Chen, X. Huang. Engineering application of membrane bioreactor for wastewater treatment in China: Current state and future prospect. Front. Environ. Sci. Eng. Vol. 8, Issue 6, pp: 805-819, 2014.
[2] W. X. Hou, G. Y. Zhang, T. X. Zhong. The application example in municipal reclaimed water of enhanced nitrogen and phosphorus removal MBR process. City and Town Water Supply, Vol. 16, Issue S1, pp:152–155, 2011 (in Chinese).
[3] A. M. Yang, Y. P. Gan, J. Chang, B. Ai, Y. Z. Peng. Process introduction of MBR of Beijing Beixiaohe reclaimed water plant. Membrane Science and Technology, Vol. 31, Issue 4, pp: 95–99, 2011 (in Chinese).
[4] X. J. Fan, L. L. Jiang, X. H. Liu. Engineering design of integrated MBR process for municipal wastewater treatment. China Water & Wastewater, Vol. 26, Issue 10, pp: 47–50, 2010 (in Chinese).
[5] Y.Y. Zhang, Y. M. Guo, B. Liu, F. Guo, Y. N. Zhang, Y. F. Zhang, Y. M. Chen. Application of 3AMBR in the fourth wastewater treatment plant of Kunming. Chinese Journal of Environmental Engineering, Vol. 7, Issue 9, pp: 3409–3414, 2013 (in Chinese).
[6] L. L. Jiang, W. L. Zhang, T. Liang, B. Hu. Study on degradation characteristics of two anoxic $A^2$O-MBR wastewater treatment system. Technology of Water Treatment, Vol. 39, Issue 1, pp: 93–96, 2013 (in Chinese).
[7] X. M. Zhang, J. Y. Hao, Q. H. Ma, D. Li. Comprehensive Analysis of 9-year Running Data of A2O-MBR in Xi'an Siyuan University. Meteorological and Environmental Research. Vol. 11, Issue 5, pp:139-143, 2020.
[8] P. Cote，Z. Alam，J. Penny. Hollow fiber membrane life in membrane bioreactors (MBR). Desalination，Vol. 88, Issue 13, pp: 145-151, 2012.
[9] F. Meng, S.-R. Chae, A. Drews, M. Kraume, H.-S. Shin, F. Yang, Recent advances in membrane bioreactors (MBRs): membrane fouling and membrane material, Water Res. Vol. 43, pp:1489–1512, 2009.
[10] B. Verrecht, T. Maere, I. Nopens, C. Brepols, S. Judd. The cost of a large-scale hollow fibre MBR. Water Research, Vol. 44, Issue 18, pp: 5274–5283, 2010.
[11] D. Li, Q. H. Wang, B. Fu, B. L. Qin, X. M. Zhang, Q. H. Ma. Final accounts and operation cost analysis of the sewage treatment and reclaimed water reuse system of Xi'an Siyuan University [J]. Water pollution and treatment, Vol. 10, Issue 1, pp: 26-34, 2022. https://doi.org/10.12677/WPT.2022.101004 (in Chinese).
[12] A. Fenu，W. De Wilde，M. Gaertner，M. Weemaes, G. de Gueldre, B. Van De Steene. Elaborating the membrane life concept in a full-scale hollow-fibers MBR[J]. Journal of Membrane Science. 421-422 (2012): 349-354, https://doi.org/10.1016/j.memsci.2012.08.001.
[13] X. S. Wang, J. H. Gao, B. Ai, Q. Fu, J. Chang, Y. P. Gan. Evaluation of membrane life span in a full scale MBR Process for reclaimed water treatment plant[J], Water Purification Technology, Vol. 33, Issue 5, pp: 24-27, 2014 (in Chinese).
[14] Y. Xu, T. Lei, J. Y. Sun, J. L. Xia, T. Xue, K. C. Yu, J. Guan, Y. L. Chen, X. Huang. Life-time assessment of membrane in large-scale MBR plant for municipal wastewater treatment[J], China Water & Wastewater, Vol. 31, Issue 5, pp: 34-39, 2015 (in Chinese).
[15] H. F. Liu, S. L. Yu, L. Gao, X. F. Song, Y. Q. Wu, M. Di. The separation performance change of ultra-filtration membrane in water treatment plant and membrane life-time prediction. Water & Wastewater Engineering, Vol. 46,

 

DOI: 10.17148/IARJSET.2022.9921

Issue 7, pp: 47-53, 2020 (in Chinese).
[16] Lin Siqing, Zhang Weirun, Sun Zhiying, et al. GB/T 20103-2006. Membrane separation technical terminology[S]. Beijing: General Administration of Quality Supervision, Inspection and Quarantine, Standardization Administration of the People's Republic of China, 2006 (in Chinese)
[17] Ma Shihao, Xu Yun, Wen Jianping, et al. CECS152: 2003. Integrated membrane bioreactor sewage treatment application technical regulations[S]. Beijing: China Engineering Construction Standardization Association, 2003 (in Chinese)
[18] China Environmental Protection Industry Association, Beijing Bishuiyuan Science and Technology Co., Ltd., Research Center for Eco-Environmental Sciences, Chinese Academy of Sciences. HJ 2528-2012. Hollow fiber membrane bioreactor set[S]. Beijing: China Environmental Science Press, 2012 (in Chinese)
[19] D. Li, H. S. Zhang, B. Fu, B. L. Qin, J. Y. Hao. Analysis of water reuse in $A^2O$ / MBR-Take Xi'an Siyuan University as an example [J]. Water supply and drainage, Vol. 43, Issue S1, pp: 163-166, 2017 (in Chinese).
[20] D. Li, J. Y. Hao, Q. H. Ma, X. M. Zhang, B. Fu, B. L. Qin. Long-term operational data analysis of the MBR process [J]. Water Purification Technology, Vol. 38, Issue 6, pp: 92-96, 2019 (in Chinese).
[21] S. H. Zhou, B. Fu, D. Li, B. L. Qin, Q. H. Wang. Study on MBR Cleaning Process [J]. Water pollution and treatment, Vol. 10, Issue 1, pp: 13-25, 2022. https://doi.org/10.12677/WPT.2022.101003 (in Chinese).
[22] D. Li, X. M. Zhang, B. Fu, B. L. Qin, Q. H. Ma. Application of big data technology in sewage MBR membrane life prediction in universities' wastewater treatment [J]. Progress in Applied Mathematics, Vol. 11, Issue 1, pp: 583-589, 2022. https://doi.org/10.12677/aam.2022.111065 (in Chinese).
[23] D. Li, X. M. Zhang, B. L. Qin, B. Fu, Q. H. Ma. Gas Float-$A^2$/O-MBR Process on Campus Wastewater Treatment-Taking Xi'an Siyuan College as an Example. Chemical Engineering and Technology, Vol.12, Issue 1, pp:32-39, 2022. https://doi.org/10.12677/hjcet.2022.121005 (in Chinese).