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Enhancement of Productivity in Reverse Osmosis Desalination Processes

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Abstract: The steady-state and periodic performances of a seawater desalination unit based on a small-scale commercial spiral-wound membrane were studied. For the steady-state case, operating pressures ranging from 30 bar to 50 bar and temperatures ranging from 22°C to 28°C were investigated. As expected, increasing the pressure resulted in improvements in the water recovery, salt rejection and energy consumed by the feed pump per m^3 of permeate produced. The improvements were larger for operation at low to moderate pressures than at high pressures. Both the permeation rate and salt rejection changed linearly with temperature; the permeate flux increased by 2.8%/°C whereas the salt rejection decreased by 0.007%/°C. For the case of unsteady-state operation, the operating pressure was varied according to a symmetric square wave function around an average pressure of 50 bar. The production rate increased as the period of the wave decreased. Such an improvement was obtained at the expense of a marginal increase in the total energy consumed. For a wave period of two minutes, the production rate increased by 8% over that obtained from steady-state operation while the energy consumed increased by a mere 0.15%. A simple theoretical analysis showed that a 12.3% improvement in the permeation rate would be obtained in the absence of concentration polarization. The salt rejection was not affected by this mode of operation.

Key words: Reverse osmosis, spiral-wound membranes, seawater desalination, membrane performance, periodic operation.

Introduction

Desalination of both seawater and brackish water is commonly used now-a-days for overcoming the huge scarcity of potable water in different parts of the world, particularly in the Middle East and North African (MENA) region. Multi-stage flash distillation and reverse osmosis (RO) are, by far, the two most widely employed methods for desalting seawater and brackish water (Wangnick, 2002; Van der Bruggen and Vandecasteele, 2002; Andrianne and Alardin, 2003; Semiat, 2000). Multi-effect distillation is another process which accounts for a significant share of the desalination market. The RO process has several advantages over the thermal processes. They include operation at ambient temperature, less energy requirements, lower initial capital cost, shorter start-up to on-line time interval, ease of operation with minimal operator training and, for a given plant output, the plot site required is much smaller. The main disadvantages of the RO process are its more stringent pretreatment requirements, susceptibility to significant swings in the production rate if the raw water quality changes and progressive performance decline due to irreversible fouling and permanent membrane compaction. Concentration polarization is another phenomenon which promotes membrane fouling and reduces the productivity of membrane processes (Bhattacharjee et al., 1999; Damak et al., 2004).

Apart from periodically cleaning the membranes, the flux may be increased by operating the process at a higher temperature and pressure at the expense of larger overall operating costs. Also, a high operating pressure results in a higher rate of fouling. Periodic operation is another method that has been found to substantially improve the productivity of the process (Kennedy et al., 1974; Colman and Mitchell, 1990; Al-Bastaki and Abbas, 1998; Abbas and Al-Bastaki, 2001). Such improvements result from the fact that periodic operation yield fluid instabilities which, in turn, disturb the flux-limiting effects of concentration polarization and fouling. Kennedy et al. (1974) showed that improvements in reverse osmosis of sucrose solution can be obtained by pulsing the feed flow over a tubular cellulose acetate membrane according to a harmonic function. At a frequency of 1 Hz, they obtained a 70% improvement in the permeate flux over steady-state operation. Colman and Mitchell (1990) employed flow pulsations and baffles to improve the permeation rates for a 1% (w/w) Dextran T500 solution. The resulting average permeation flux was about 1.5 to 2 times higher than that corresponding to unbaffled steady axial flow. Al-Bastaki and Abbas (1998) obtained a 13% increase in the permeation flux by varying the feed pressure of a simulated brackish water (10 kg NaCl per m^3 of distilled water) to an old FilmTec BW30 membrane which was in operation for over four years. Cyclic operation has been found to produce significant improvements over steady-state operation for a variety of other processes including chemical reactors, distillation, adsorption and heat exchangers (Silveston, 1991; Winzeler and G. Belfort, 1993; Spiazzi et al., 1993; Douglas, 1972; Erkoç et al., 2002; Lange et al., 2004; Lau et al., 2004).

The objective of this work is to investigate the steady-state and periodic performances of a small-scale seawater desalination unit which is based on a new FilmTec SW30-2521 membrane. In the first part, experiments are conducted to study the effects of two key operating parameters, namely the feed pressure and temperature, on the steady-state performance of the process in terms of water recovery, salt rejection and power consumption. In the second part, the effectiveness of operating the plant in an unsteady-state manner by varying the feed pressure according to a symmetric square wave is determined.

Experimental Setup and Procedure

A schematic diagram illustrating the major features of the RO desalination unit used is shown in Figure 1. A 1.3 kW pump draws the feed solution from a 340 litres PVC feed tank through a 10 μ cartridge filter and a manual valve, V1, and delivers it at a high pressure to an SW30-2521 FilmTec membrane. The characteristics of the membrane along with the nominal operating conditions are listed in Table 1. It is a new spiral-wound thin film composite type that has been in operation, prior to this investigation, treating tap water for about 30 hours. The membrane is placed in a GRP shell with 61 mm diameter and a length of 457 mm. Each of the two streams (permeate and brine) leaving the membrane passes through a rotameter before entering a collection tank. The rotameters were used to provide qualitative measures of the flow rates; actual flow rates were measured with a stop watch and a graduated cylinder. The membrane inlet and outlet pressures were measured using Bourdon tube gauges. The feed tank is fitted with a heating coil to control the feed temperature. The conductivities of the feed, permeate and brine were measured off-line using a Jenway Model 4310 conductivity meter. The concentration of the solute was then read from available conductivity-concentration calibration curves.

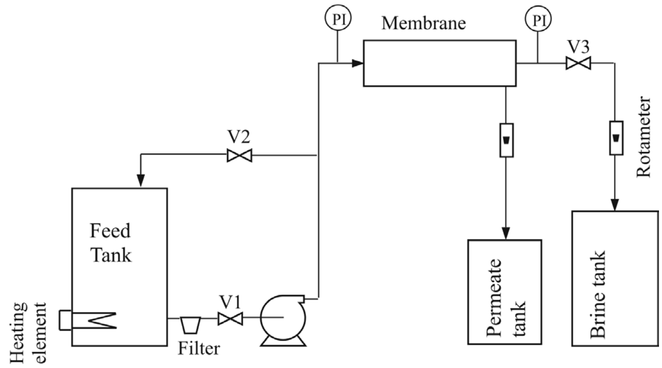

Figure 1: Schematic of the experimental rig.

Table 1: Nominal feed conditions and membrane characteristics

Parameter	*Value*
Feed conditions	
Flow rate, Q_f	0.470 m^3/h
Salt concentration, C_f	30 kg/m^3
Temperature, T	25°C
Pressure, P	50 bar
Membrane characteristics	
Membrane type	Dow/FilmTec SW30-2521
Membrane configuration	spiral-wound
Active surface area	1.2 m^2
Maximum feed rate	1.36 m^3/h
Minimum brine rate	0.23 m^3/h
Maximum operating pressure	69 bar
Maximum operating temperature	45°C
pH range, continuous operation	2-11

This experimental set-up allows independent setting of the feed pressure, temperature and concentration for each experiment. The operating pressure is regulated using a manual valve, V3, installed in the brine line close to the membrane. Valves V1 and V2 are used for adjusting the feed flow rate.

The feed solution was prepared by mixing sodium chloride (NaCl) with distilled water to simulate seawater having a salinity of 30 kg salt/m^3. At the beginning of each experimental test, the feed tank was charged with 320 litres of solution which is sufficient for a continuous run of about 40 minutes. The duration of each experimental run was divided into two parts. The first 10 minutes, after start-up, was used for allowing the process to reach equilibrium. This was followed by a period during which the product is metered and all required measurements performed. This period was 30 minutes for the steady-state runs and 24 minutes for the cyclic experiments. Twenty four minutes only were used for the periodic operation so as to obtain an integral number of time-periods for all the runs performed.

Theory

A number of mathematical models are available that describe the behaviour and performance of the RO process. For the sake of clarity and completeness, the mathematical relations used in this work are presented in this section.

The overall water and salt mass balance equations around the membrane are:

$$Q_f = Q_b + Q_P \tag{1}$$

$$Q_f C_f = Q_b C_b + Q_P C_P \tag{2}$$

where subscripts *f*, *b* and *p* refer to the feed, brine and permeate streams. Q (m^3/h) and C (kg NaCl/m^3) refer to the flow rate and salt concentration respectively.

The transport of solvent and solute is well described by the most widely used solution-diffusion model (Sourirajan, 1970; Soltanieh and Gill, 1981; Rautenbach, 1986). The water permeation rate, Q_p, is given by:

$$Q_P = SA(\Delta P - \Delta\pi) \tag{3}$$

and the salt passage rate, Q_s (kg NaCl/h), is given by:

$$Q_s = SB(C_m - C_P) \tag{4}$$

where ΔP (bar) is the pressure difference between the feed side of the membrane and the permeate side ($\Delta P = P - P_P$). In this study, the permeate side is maintained at atmospheric pressure, i.e. $P_P = 0$. Similarly, $\Delta\pi$ is the osmotic pressure difference between the feed side and the permeate side of the membrane ($\Delta\pi = \pi_m - \pi_P$). Subscript *m* refers to the membrane surface. S (m^2) is the membrane active surface area. A ($m \cdot h^{-1} \cdot bar^{-1}$) and B (m/h) are the water and salt permeability coefficients. These two parameters are generally not given by the membrane manufacturers. They have to be determined experimentally.

The salt passage rate may also be calculated from the permeate flow rate and concentration:

$$Q_s = Q_P C_P \tag{5}$$

The osmotic pressure varies with the concentration of the solute and temperature. The following correlation may be used to estimate the osmotic pressure of sodium chloride-water system at 25°C:

$$\pi = 7.684 \times 10^{-4} C + 4.048 \times 10^{-10} C^2, \quad 0 \le C \le 50 \tag{6}$$

with π in bar and C in kg NaCl/m^3. This correlation was developed through curve fitting data given by Sourirajan (1970).

Results

Steady-state Performance

Initially, steady-state experiments were performed using a range of operating gauge pressures (30–50 bar) and three different feed concentrations (distilled water, 10 kg NaCl/m^3 and 30 kg NaCl/m^3). Experiments were made with distilled water as they are necessary for estimating the water permeability of the membrane whereas those corresponding to a feed concentration of 10 kg NaCl/m^3, which represents a brackish water with a relatively high salinity, are useful for illustrating the effect of the feed concentration on the performance of the plant. The results are presented in Figure 2 which

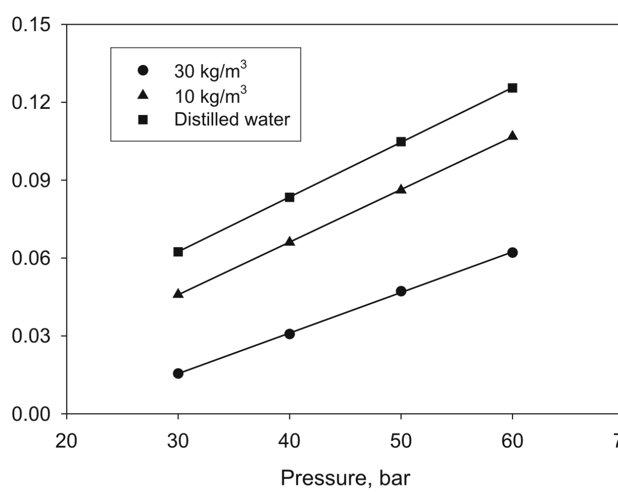

Figure 2: Effects of the feed pressure and concentration on the permeation rate.

shows the variation of the production rate with both the feed pressure and concentration. Note that all of the experimental values reported in this study were obtained by averaging the results of two repeated runs. In addition, all repeated runs lead to results which were in close agreement.

Figure 2 shows that the production rate increases linearly with the feed pressure. For a feed concentration of 30 kg NaCl/m^3, increasing the pressure from 50 bar to 60 bar improves the permeation rate by 31.6% (from 4.72 $\times 10^{-2}$ m^3/h to 6.21 $\times 10^{-2}$ m^3/h). If the feed pressure remains constant, the production rate decreases with increasing feed concentration due to the higher osmotic pressure. As an example, at a feed pressure of 50 bar, the plant produces about 83% more permeate for a feed concentration of 10 NaCl/m^3 than that produced if the feed concentration is 30 kg NaCl/m^3. Note that since the SW30-2521 membrane was designed for seawater desalination a feed with a concentration of 30 kg NaCl/m^3 was employed in all the experimental work and results to follow.

Water recovery (WR) and salt rejection (SR) are two measures generally used for reporting the performance of RO processes. They are given by:

$$\mathrm{WR}(\%) = \frac{Q_P}{Q_f} \times 100 \tag{7}$$

and

$$\mathrm{SR}(\%) = (1 - C_p/C_f) \times 100 \tag{8}$$

Figure 3 illustrates the effects of the operating pressure on the water recovery and salt rejection. As expected, both performance measures increase with increasing pressure as more water is pushed through the membrane while the latter acts as a barrier to the salt. However, above a certain pressure (about 50 bar), the rate of increase in the salt rejection drops rapidly and eventually a plateau is expected to be reached where the salt rejection no longer increases as the high pressure pushes the salt together with the water permeating through the membrane. Increasing the operating pressure from 50 bar to 60 bar improves the salt rejection by 0.1%.

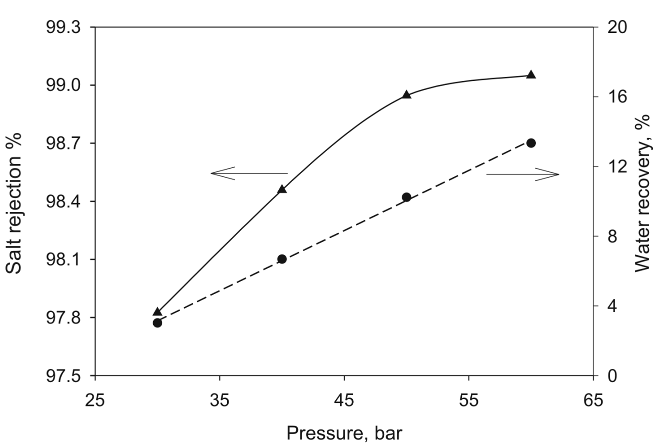

Figure 3: Variation of the water recovery and salt rejection with pressure.

The effects of temperature on the water recovery and salt rejection are shown in Figure 4. For the considered temperature range (22°C to 28°C) both measures vary linearly. The recovery increases while the salt rejection decreases due to the higher diffusion rates of both the water and salt. The water production increases at an average rate of about 2.8%/°C which is well within the expected range of 2% to 3% per °C. The salt rejection drops by 0.007%/°C.

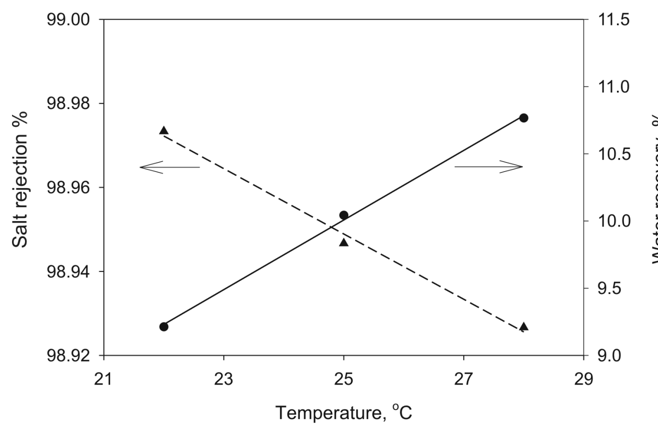

Figure 4: Effects of temperature on water recovery and salt rejection.

To investigate the energy requirement, a digital electric energy meter was used to measure the energy consumed by the feed pump during each experimental run. The results are presented in Figure 5 which shows that the higher the pressure the smaller the amount of energy consumed per m^3 of permeate produced. The rate of reduction is steeper at low to moderate pressures than at high pressures. The energy consumed per m^3 of permeate produced at 60 bar is 18.1% lower than that consumed at 50 bar. In practice, a number of factors are considered in setting the highest operating pressure including membrane type, membrane fouling, the desired production rate and the energy consumed. The latter is not the determining factor as most of the energy delivered by the feed pump (over 90%) is recovered from the brine leaving the plant by the energy recovery system.

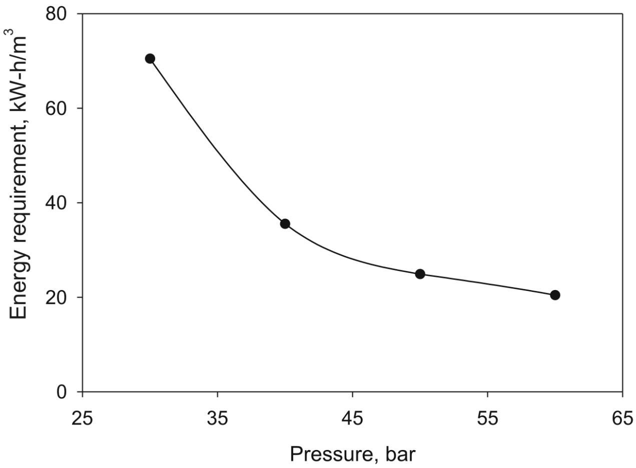

Figure 5: Variation of the power consumed with the feed pressure.

Periodic Operation

As stated earlier, concentration polarization is one of the factors which limit the performance of RO processes by increasing the osmotic pressure and hence reducing the driving force for the water permeation rate. The increase in the water production rate in the absence of polarization may be estimated by solving Equations (1) to (6) simultaneously with the concentration at the membrane wall, C_m, replaced by the average bulk concentration: $C_{av} = (C_f + C_b)/2$.

In addition to the specified feed conditions and membrane active surface area given in Table 1, solution of the system of equations describing the behaviour of the process requires knowledge of the water and salt permeability coefficients, *A* and *B*. First, *A* is determined from the distilled water experimental data presented in Figure 2 and Equation (3) with $\Delta\pi = 0$. Then, Equations (3), (4) and (6) are used together with the experimental data corresponding to the considered feed concentration, namely 30 NaCl/m^3 to estimate *B*. The values obtained for *A* and *B* are 1.76×10^{-3} m/(h·bar) and 3.17×10^{-4} m/h respectively. Equations (1) to (6) with C_m replaced by C_{av} were then solved iteratively using the Wegstein method (Luyben, 1990) to estimate the water permeation rate in the absence of concentration polarization. The value obtained is $Q_p = 5.30 \times 10^{-2}$ m^3/h which is about 12.3% higher than the experimental value of 4.72×10^{-2} m^3/h. This means that a significant improvement in the plant productivity can be obtained if some means is employed to promote mixing in the feed channel and hence reduce concentration polarization.

Cyclic variation of the operating pressure is an approach that is used here to continuously disturb the polarization layer. The pressure is varied according to a symmetric square wave as shown in Figure 6, where τ and *M* are the period and amplitude of the wave respectively and *P* is the average value of the periodic input which is equal to the value of the feed pressure under conventional steady-state operation. Note that the sine wave is another type of forcing function that can be used. However, the simpler square wave function has been shown to be a better input as it produces the most abrupt disturbance (Douglas, 1970; Fjeld and Kristiansen, 1969).

Figure 7 presents the effects of the time-period of the wave on the average permeation rate for cyclic operation of the process with an amplitude of 10 bars around an average pressure of 50 bar. Each data point in this figure is the average of two repeated experimental runs. The duration of each run was 24 minutes. The results show

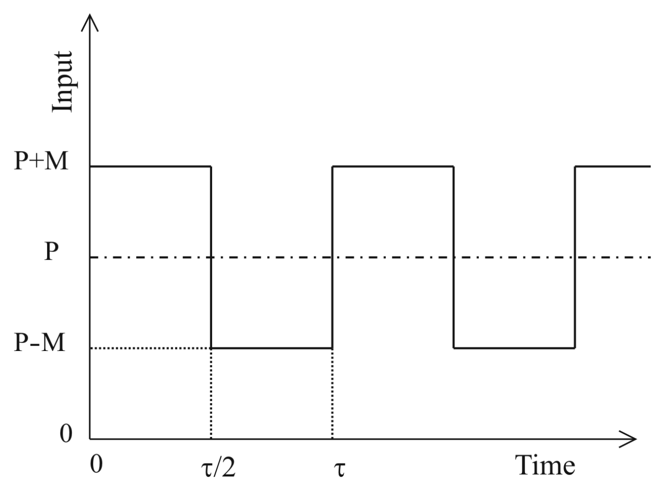

Figure 6. Periodic operation strategy.

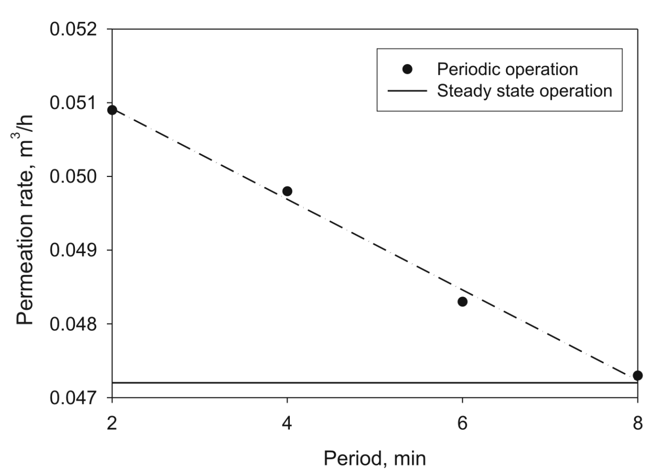

Figure 7. Effects of periodic operation on the process productivity for an average pressure of 50 bar and an amplitude of 10 bar.

that the quantity of permeate produced increases as the period of the oscillations is decreased. The smallest period considered (τ = 2 minutes) lead to an improvement of about 8% in the permeation rate over that obtained from steady-state operation. The use of smaller time periods is expected to lead to further improvements. As the process is manually controlled, it was not possible to generate such relatively high frequency square waves. The equipment is to be modified such that the operating pressure and feed flow rate will be set through a computer. This will allow the investigation of the effects of high frequency cyclic changes in either of these two key operating parameters. Measurements of the power consumed showed that the extra power required to operate the pump in a periodic manner was marginal. For example, the energy consumed by the pump during cyclic operation at a period of two minutes was only 0.15% larger than that consumed during steady-state operation. This result confirms the findings of Ilias and Govind (1990) who, using a theoretical analysis, reported that the excess energy requirement for periodic operation is a minute fraction of that required for steady-state operation.

Intuitively, due to depolarization of the membrane, one expects that the salt rejection would improve with cyclic operation. This was not the case as virtually all periodic tests produced the same rejection as that corresponding to the steady-state mode of operation (about 98.94%). This result agrees with that obtained by Kennedy et al. (1974). They found that the flow oscillations did not affect the concentration of the solute in the permeate for reverse osmosis of a 10% (w/w) sucrose solution; in all of the considered cases (various periods and amplitudes), the permeating fluid contained 0.2% (w/w) sucrose.

In addition to concentration polarization, a second factor that limits the permeation rate is membrane fouling. Periodic operation is known to disturb both of these factors. Therefore, it is expected that if an actual seawater solution was employed then the improvement in performance due to periodic operation will be higher than the 8% obtained with the clean water-sodium chloride solution.

Conclusions

The steady-state and periodic performance of a small-scale commercial seawater desalination membrane treating a feed containing 30 kg salt/m^3 was investigated. For the steady-state case, as expected, the product quantity and quality as well the energy consumed by the feed pump per unit permeate improved with increasing pressure. For example, increasing the operating pressure from 50 bar to 60 bar led to an increase of 31.6% in the permeation rate, an 18.1% reduction in the energy consumed by the feed pump per m^3 of permeate and an increase of 0.1% in the salt rejection. Larger rates of improvement were obtained at low to moderate operating pressures. As for the effects of temperature, the permeation rate was found to increase linearly by 2.8%/°C while the salt rejection decreased again linearly by an average of 0.007%/°C.

Operating the plant in a cyclic manner by varying the pressure according to a symmetric square wave function resulted in significant increases in the permeate flux. The quantity of the permeate increased as the period of oscillations was decreased. Upto 8% improvement in the production was obtained at the expense of a mere 0.15% increase in the total energy consumed by the feed pump. A theoretical analysis showed that the improvement in the permeation rate would be 12.3% in the absence of concentration polarization, i.e. perfect mixing of the feed channel. As for the product quality, the salt rejection was not affected by such a mode of operation. Finally, it is expected that as cyclic operation reduces both concentration polarization and membrane fouling, then by using actual seawater the percentage improvement in performance will be higher than that obtained with the clean water-sodium chloride solution employed in this study.

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