学　位　論　文　内　容　の　要　旨

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学　位　論　文　題　名

Development of a system for nutrients recovery from hydrolyzed urine by forward osmosis concentration
(正浸透法による加水分解尿からの栄養塩回収システムの開発)

Human urine is nutrients-rich resource as it contains the major part of nutrients e.g. nitrogen, phosphate, potassium found in domestic wastewater. Large quantities of urine are produced continuously, especially in populated areas, making available a continuous supply of nutrients. Therefore, urine has the potential to be reused in agriculture as a liquid fertilizer. However, urine contains 95% of water giving bulky volume and low concentration of nutrients. So, urine storage and transport prior to application in farmland is non-economically competitive with chemical fertilizers and renders its reuse challenging. Hence, urine volume reduction and nutrients concentration appear to be necessary. Earlier studies suggested 80% volume reduction as a minimum requirement to be cost effective. Several volume reduction techniques were reported in the literature. However, they are all energy demanding processes, making the concentration of urine non-advantageous. Forward osmosis process is an emerging technology used in several applications for volume reduction and concentration and is reported to consume less energy than other concentration alternatives e.g. reverse osmosis, evaporation... In this study, we propose a nutrients recovery system with urine volume reduction by forward osmosis process from urine. The FO volume reduction technique is an osmotic pressure driven process where water molecules move across a semipermeable membrane from a feed solution of low solute concentration to a draw solution of high solute concentration. Moreover, solutes in the solutions can diffuse from one compartment to another by their concentration differences. The objectives of this research were to develop a mathematical model for water and solutes flux estimation during urine volume reduction and to design a nutrient recovery system with forward osmosis concentration process.

In chapter 1, the problems on sanitation all over the world, potential of urine as a fertilizer, crisis of natural resources, resource oriented sanitation, forward osmosis applications and the phenomena involved in the membrane separation process were reviewed. The issues that should be assessed were identified and the objectives of the thesis were summarized.

In chapter 2, the phenomena that occur during forward osmosis process were studied. Experiments were carried out 1) to assess the water flux performances of real and synthetic hydrolysed urine, 2) to evaluate the solute diffusion, 3) to assess the adequacy of the solute activity for the calculation of water flux, and 4) to identify the major solutes for water flux estimation during the volume reduction process. A hydrolysed synthetic urine and hydrolysed real urine were used as a feed solution, and sodium chloride solution with concentration range of 3-5 mol/L was a draw solution. The solutes activities was calculated with PHREEQC from the molar concentrations. As a result, it was found that: 1) the volumes of real and synthetic urine could be concentrated to 2-5 times with 3-5 mol/L sodium chloride solution, 2) ammonia and the inorganic carbon in urine easily diffused to draw solution through the membrane, 3) solute activities in the feed and the draw solutions were suitable for the estimation of the osmotic pressure, and 4) the organic matter presented in real hydrolyzed urine had a negligible effect on the osmotic pressure variation.

In chapter 3, a multicomponent mathematical model was developed to describe the phenomena during forward osmosis process. The model considered the advection, diffusion and activities of the solutes in feed and draw solutions through a semi-permeable membrane. Partial differential equations were established to estimate the concentration variation across the membrane and in the bulk solutions. The finite difference approximation of the partial derivatives was applied to numerically solve these equations, then the differential equations were described with Crank Nicholson scheme. The obtained systematic non-linear equations were solved with the Newton-Raphson method at each time step. The solute diffusivities and pure water permeability of the membrane were required for the simulation. These parameters were calibrated by the experimental data with single salt solutions as a draw solution and pure water as a feed solution. The experimental conditions were simulated and compared with the experimental results. Least square method with Nelder mead algorithm was used to find the best fit of the volume and concentration curves for the diffusivities estimation. The model was later validated by comparing simulated and other forward osmosis experiments results using synthetic hydrolyzed urine and sodium chloride draw solution. The important outcomes of this research are that: 1) the simulation of the model was succeeded to estimate the evolution of volume and solute concentrations in both solution, 2) ammonia can diffuse from urine to draw solution to show the lower concentration factor than feed solution volume reduction factor, and 3) the nutrients concentration profile inside the membrane was calculated to show the effect of the internal concentration polarization which reduced the osmotic pressure at the active layer surface to 35% of its initial value.

In the chapter 4, a reactor to be implemented for urine concentration was designed. The developed model was used to evaluate the required volume of draw solution to concentrate hydrolyzed urine into 1/5 of its initial volume and the maximum recovery ratio of nutrients. The relationship among initial osmotic pressure and volume of draw solution, and effective membrane area was obtained by the simulation. Two levels of membrane areas, which were 300 and 400 cm2, were selected for detailed discussion. The results show that: 1) 8.5 L and 0.16 L of initial draw solution volumes are required to concentrate 1L of hydrolysed urine respectively for 7 MPa and 33 MPa initial osmotic pressure with 300 cm2 membrane area. The volumes decrease to 2.5 L for 7 MPa and 0.15L for 33MPa with an increase of the membrane area to 400 cm2. 2) In the 1/5 volume reduction cases, 15.8% - 26.9% of ammonia, 76% - 85.5% of potassium and 94.7% - 97% of phosphate will be able to be recovered. 3) A volume reduction to 1/2.8 will be adequate to maximize the recovery of ammonia to 70% with 300 cm2 membrane area but further analysis is required to fulfill both the 1/5 volume reduction and maximizing ammonia recovery.

In the chapter 5, the main findings and recommendations related to the application of forward osmosis process for a concentration and sustainable reuse of urine liquid fertilizer in agriculture level were summarized.