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学位論文題名

Design of an onsite volume reduction system for source-separated human urine

（排水分離分散型処理システムにおける分離尿濃縮装置の設計）

学位論文内容の要旨

This study was carried out to resolve transportation of human urine from household to the farmland. We proposed an onsite volume reduction system (OVRS) to treat source-separated human urine at household level as part of the onsite wastewater differentiable treatment system (OWDTS). The OVRS is based on a vertical gauze sheet in permanent contact with urine, which is placed over a urine collection tank. The water from the urine tank is expected to flow vertically upward in the gauze sheet through various small capillaries under the capillary pressure, which is then evaporated into the atmosphere through the sheet surface. The specific goal of this research work is to establish comprehensive design procedures to estimate size of the gauze sheet of the OVRS for various climate conditions.

In Chapter 1, comprehensive literature review was carried out to summarize the present research work done on urine treatment and what are the issues that should be addressed.

In Chapter 2, a case study of Southern Pakistan was carried out to estimate transportation cost of human urine from household to farmland using local trucking system, which revealed that the cost increases significantly when the transportation distance increases. Therefore, a high rate of 80%volume reduction of urine per day was proposed at each household level to provide incentives to farmers to switch to urine-based fertilizer instead of commercial fertilizer. Therefore, we proposed a laboratory-scale OVRS unit.

In Chapter 3, a water transport model of a cloth sheet was developed, which is based on water balance in the sheet comprising water supply to the sheet and water evaporation through the sheet surface. The performance of this model was evaluated using laboratory-scale onsite volume reduction unit. The experiment were designed and performed to evaluate the water penetration through the sheet and water evaporation. The effect of air temperature, humidity and air flow rate on mass transfer coefficient was investigated using a synthetic urine and de-ionized water respectively. The mass transfer coefficient was represented in a non-dimensional form of Sherwood Number (Sh) and a relationship between Sherwood Schmidt and Reynolds Numbers was established. The important outcome of this study was confirmation of the water transport model and establishment of comprehensive design procedure to estimate size of the gauze sheet for OVRS. Then, the design procedure was applied to the conditions of Southern Pakistan to estimate size of the actual gauze sheet required for 80% volume reduction of 10 L urine per day. The major finding was that a small size of 440-2060 cm^2 was required for operating this system at household level.

In Chapter 4, the performance of the onsite volume reduction system using synthetic urine with various concentrations, such as 10% diluted synthetic urine (4.177 g salt L^{-1}), undiluted synthetic urine (41.77 g salt L^{-1}), twice (83.54 g salt L^{-1}), thrice (125.31 g salt L^{-1}) and four times (167.08 g salt L^{-1}) concentrated synthetic urine was evaluated to investigate the effect of salt concentration on the parameters of the existing water transport model. The new finding was that the water penetration into the gauze sheet was not affected by the salt concentration of synthetic urine. But the saturated vapour pressure drop occurred in evaporation experiment, which is attributed to high salt concentration of synthetic urine. Accordingly, the existing design procedure was amended by incorporating the procedure for calculating the saturated vapour pressure based on the Raoult's Law and the solubility of salts.

Then, the modified design procedure was applied to assess feasibility of the onsite volume reduction system for various climates to treat 80% volume of 10 L urine per day. The results showed that OVRS requires suitably small area if it is to be installed in arid and tropical climate regions. While the areas located in the temperate and cold climates require relatively larger size of the sheet, thus making the system not effective for those conditions.

In Chapter 5, it is explained that urea hydrolysis of human urine can take place causing release of ammonia

emission in the air resulting into significant environmental pollution. To resolve this issue, various methods have been reported such as addition of calcium and magnesium salts, addition of acids etc. to control the urea hydrolysis. One study conducted on urea hydrolysis in soil reported that rate of urea hydrolysis in the soil solution increased with an increase in urea concentration until a maximum was reached; at higher urea concentrations, the rate of urea hydrolysis decreased. Keeping in view this assumption, simple storage experiments were performed to investigate the effect of high concentration of synthetic urine comprising a mixture of salts, urea and creatinine on inhibition of urea hydrolysis. For this purpose, various concentrations of synthetic urine containing twice, four times, six time and eight times concentrations with a fecal contamination at 25°C were used. The pH of the samples was measured periodically as it is an indicator of the urea hydrolysis. The important finding is that the concentration of urine containing the mixture of salt, urea and creatinine amounting to 227-334 gL^{-1} in the synthetic urine controlled hydrolysis, while the concentration less than 227 gL^{-1} did not control of hydrolysis.

In Chapter 5, it is also explained that the previously obtained data from short duration experiments of 90 hrs is not sufficient to decide the sheet replacement frequency, so as to maintain the steady-state evaporation for a long time of months. Therefore, long-term operation of the OVRS was performed for 80 days to evaluate the water evaporation efficiency of the same gauze sheet. This was done to make sure whether and when the salt accumulation in the gauze sheet is going to inhibit the water evaporation rate, so as to fix the sheet replacement frequency. The main finding is that salt accumulation in the sheet or in the urine did not inhibit hydrolysis while using the same sheet. Therefore, this system can be operated for longer period of 2-3 months maintaining the same performance level.

In Chapter 5, it is further explained that high salt concentration contained in the synthetic urine can significantly control urea hydrolysis, therefore, the experiments were performed to evaluate the fate of nitrogen during volume reduction of urine using the onsite volume reduction system. For this purpose, the OVRS unit was operated under low as well as moderate evaporating conditions. The concentrations of urea, ammonia and salt in the liquid as well as air were measured periodically particularly for the moderate evaporating condition as the rapid salt accumulation can be anticipated in such condition which may affect hydrolysis. Likewise, pH for the both conditions was also measured periodically. While operating the OVRS unit for moderate evaporating conditions provided rapid accumulation of significant amount of the salt in the tank resulting into inhibition of urea hydrolysis. No offensive odour and the ammonia loss in the air were observed inside the onsite volume reduction unit. On the contrary, pH of the synthetic urine increased to 8.9 indicating the early urea hydrolysis causing offensive odour and the ammonia loss in the air while operating the system at low evaporating conditions.

In Chapter 6, the preliminary guidelines related to design and operation of the OVRS has been discussed.

In Chapter 7, the main findings of the study have been summarized.

The following contribution could be made for ensuring sustainable sanitation towards society:

- The OVRS is a new method to treat human urine at household level for small communities to ensure sustainable sanitation in compliance with the UN Millennium Development Goal No: 7C.
- This system is based on the natural atmospheric energy to resolve its transportation by trucking. 2 m/s wind velocity is small enough to be obtained in a wind tunnel to evaporate urine using a small size of the gauze sheet. Thus, it will contribute towards sustainability.
- The water transport model and design procedures of the OVRS have been established, which can be used for estimating the size of the sheet for any climate conditions. Thus, the system could be applicable for local conditions.
- By 80% volume reduction of urine per day, we can obtain high concentration of urine in a short time that provides control of hydrolysis, thus avoiding the pollution in the air and public concern.
- The same gauze sheet can be used in the actual scale OVRS for 2-3- months without any inhibition.

学位論文審査の要旨

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（排水分離分散型処理システムにおける分離尿濃縮装置の設計）

排水処理を単なる処理から資源回収型へ転換することが求められている. ここで回収する資源とは水資源に加え, 排水中の窒素やリンといった栄養塩類である. また, 排水系のうち, 管路ネットワークに係る初期投資や維持管理費用が膨大になることから, 管路ネットワークに依存しない仕組みの開発も緊急の課題として認識されている. このような課題に対して, 排水を発生源において分離し, かつ処理・資源回収する排水分離分散型排水処理法が一つの解決策を与える. 本研究は, 排水分離分散型排水処理法のうち, 分離した尿を対象としている.

分離回収した尿中には肥料成分が高濃度で含まれており, 直接農業利用や肥料原料とすることができる. しかし, 尿の利用にあたってはその輸送コストが尿利用の全体のシステムを左右しているが現状である. このため, 低コストかつ自然エネルギーを利用した尿濃縮技術の開発が望まれてきた. 本研究では, ガーゼ状の布を尿に浸漬し, 自然換気により得られる空気流により布面の水分を蒸発させる, 尿濃縮装置を考案し, その反応工学的な解析結果を用いた設計法を提案している. 本論文は以下の7章より成る.

第1章では, 本研究の背景, 目的を議論し, 現状の尿処理・濃縮法に関する最新知見の整理から, 自然エネルギーを用いる方法の必要性を強調している.

第2章ではパキスタン南部を対象に, 尿の輸送コストと市販肥料価格の比較により, 必要濃縮倍率に関する検討を行っている. その結果, 尿の利用にあたっては, その輸送コストの低減が重要であり, 対象とした地域では約5倍濃縮する必要性が示されている.

第3章では, 尿だめからガーゼへの毛管力による輸送モデルとガーゼ表面における水の蒸発モデルを組み合わせた, ガーゼ層における液面高さと水分蒸発量を表現するモデルが提案されている. 毛管力による水輸送モデル中のパラメータを求めるために実施した実験結果とモデルの妥当性の検討結果が示されている. 水分蒸発量モデル中の物質移動係数については, その風速, 空気の温度・湿

度の影響を詳細に検討した風洞実験について示され，物質移動係数について,Sherwood Number と Reynolds Number を用いた無次元表示により，すべてのデータが整理されることを示している．

第 4 章では，尿中水分の蒸発に伴いガーゼ表面に蓄積する塩分の水輸送ならびに蒸発に対する影響について検討している．蒸留水，水道水，種々の濃度の人工尿 (10 倍希釈から 6 倍濃縮の範囲) を用いた実験の結果から，輸送される液体の塩分濃度，ならびにガーゼ表面の塩分量は水輸送特性をほとんど変化させないことを示している．一方，人工尿中の塩分は蒸発速度を低下させ，この蒸発速度低下は人工尿中塩分濃度には影響されず，尿中塩分濃度にかかわらず一定の蒸発速度低下が観察されることを示している．加えて,(1) この蒸発速度の低下は飽和蒸気圧が塩分濃度により低下することによること,(2) 溶解度積を用いたガーゼ上析出塩の組成推定を用いた飽和蒸気圧低下計算により，蒸発速度が塩分の影響を受けて低下することを表現できることを示している．

以上のようにして開発されたモデルを用いて，所定の尿を所定の体積まで濃縮するために必要なガーゼの必要面積を対象とする地域の気候条件を考慮して求める本装置の設計法を構築している．特に本装置が有効である気候帯として，乾燥帯と熱帯を挙げている．

第 5 章では，尿の蒸発濃縮過程で問題となる，尿素の加水分解に伴うアンモニア態窒素の生成の制御方法について検討している．尿素の加水分解が微生物作用であることに注目し，高濃度の塩分による加水分解抑制に関する実験より，尿を 5 倍濃縮した条件に相当する塩分濃度では，アンモニアの発生を抑制できることを見出している．

また，ガーゼ上に蓄積した塩分が尿の濃縮に与える影響やガーゼの交換頻度を検討するために,80 日間の長期運転を実施した結果より,(1) ガーゼ表面の塩は短い間隔で表面より脱落し，水分の蒸発効率は変化することなく，長期間の運転においてもガーゼ交換を行う必要がないこと,(2) 尿だめの塩分濃度が上昇し，尿素の加水分解を抑制することができ，アンモニア揮散による窒素ロスを抑制することができることを示している．これらの結果より，本装置は十分な実用性を有していると結論づけている．

第 6 章では，上記で得られた結果をもとに，尿濃縮装置の設計ならびに運転操作に関するガイドラインを与えている．

第 7 章には本研究で得られた主要な成果が整理され，将来の展望が述べられている．

これを要するに，著者は排水分離分散型排水処理において，分離回収した尿の蒸発・濃縮装置を考案し，その反応工学的な解析により装置の設計・運転管理法を提案している．これらの業績は排水処理工学に対して貢献するところ大なるものがある．よって，著者は，北海道大学博士 (工学) の学位を授与される資格あるものと認める．