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A computational design of a magnetic field applied to control magnetic adsorbent used in liquid/gas adsorption processes ☆

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ABSTRACT

Recently in our research studies, ferroferric oxide magnetic micro particles were used as seeds combined with chitosan and activated carbon respectively in a nutrition recovery process for post hemodialysis (HD) and in a mixed-gas adsorbate analysis. Initially, these magnetic adsorbents used in the experiments were all sealed inside a cylinder vessel by molecular sieve filters. However, this design led to a very slow liquid or gas flow rate during adsorption. To increase the flow rate, a novel design applying a nonlinear gradient magnetic field in the reverse direction of liquid or gas flow was proposed in this paper. The objective of the design was to retain the magnetic adsorbent inside the vessel maintaining a high flow rate. The magnetic field inside an infinite solenoid coil was derived using Ampere Circuit Law and the Langevin equation. An equation, showing the relationship between the ampere-turns of the magnetic field and their positions, was outlined in this paper. We finally proved that this equation is suitable for the practical design of a magnetic field with finite length. Thus, this mathematic model could help the development of adsorption device utilizing magnetic particles.

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1. Introduction

For a two-phase (such as solid–gas phase, solid–liquid phase, solid–solid phase, liquid–gas phase, or liquid–liquid phase) system, the physical definition of adsorption is the change of density or concentration of the solute between the interface of two phases. The substance that is adsorbed is called “adsorbate”. The substance that has an adsorption function is called “adsorbent”. The general meaning of adsorption is the story of adsorption phenomena between the interface of solid and gas or liquid. According to the bonding strength of molecules between adsorbent and adsorbate, adsorption can be categorized into two classes: physical adsorption and chemical adsorption. Physical adsorption is induced by molecular interactions. Thus, their bonding strength is relatively weak. Correspondingly, isosteric heat is minor such that adsorbate can be easily desorbed (such as gas adsorption by activated carbon). Chemical adsorption is caused by chemical reaction. Due to the change of a chemical bond, chemical adsorption is irreversible and the isosteric heat release is enormous.

Currently, both solid–liquid and solid–gas adsorptions are involved in our research studies. To describe the solid–liquid chemical adsorption processing inside our novel re-absorption dialyzer, we should initially review the clinical hemodialysis (HD) process. In severe kidney ailments which make the dysfunction or malfunction of a human kidney, the patient must either be treated with hemodialysis therapy or undergo renal transplantation. In the therapy of hemodialysis, the dialyzer acts as a substitute to a human kidney. It cleans out the metabolic wastes from human blood by a dialysate solution as well as maintains the electrolyte stability inside a human body. A cylindrical device shown in Fig. 1 describes an anatomic map of a hollow fiber dialyzer. The device has two compartment spaces: the space inside hollow fibers holding the blood and the space outside the hollow fibers holding the dialysate solution. These two compartments are separated by a porous membrane which makes the wall of each hollow fiber to shield the blood. With this porous membrane, the compartment flows can exchange their mass through an ultra-filtration process. Because of its biomechanical functionality, this kind of device is also called “artificial kidney.” Previous studies [1–9] outlined the details of this ultrafiltration process. However, during HD, not only the waste molecules such as urine and creatinine are removed from the blood, but also parts of nutritional molecules (some of them are a living requirement, such as amino-acids) are also carried away. Experimental results [10] listed in Table 1 showed that the concentrations of eight essential amino-acids of a group of patients (9 males and 6 females, age ranging from 31 to 68) were reduced by about 17%–50% after HD. This causes a transient nutritional loss for a patient. The loss could be permanent if these essential amino-acids were not recovered from further nutritional supplement treatments since they cannot be synthesized inside the

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Nomenclature

$\vec{B}$	magnetic strength
$\vec{f}_b$	buoyancy
$\vec{f}_d$	drag force
$\vec{f}_g$	gravity force
$\vec{f}_h$	pressure force
$\vec{f}_m$	magnetic force
g	gravitational acceleration
$\vec{H}$	magnetic intensity
H	magnitude of magnetic intensity
H_{eff}	effective magnetic intensity
$\nabla\vec{H}$	gradient of magnetic intensity vector
∇H	gradient of magnetic intensity
I	conduction current inside solenoid coil
k	Boltzmann's constant
L	length of a solenoid coil
$\vec{m}_p$	magnetic moment per unit volume
$\vec{M}$	magnetization intensity
M	magnitude of magnetization intensity
M_∞	saturation magnetization
$n(z)$	Ampere turns
R	radius of a solenoid coil
T	temperature
v	volume of magnetic particle

Greeks

$\sigma_{particle}$	particle density
$\sigma_{solution}$	solution density
(z, ρ, ϕ)	cylindrical-coordinate system
μ_0	vacuum magnetic permeability
$\vec{\delta}$	unit vector that parallels to $\vec{f}_m$
γ	$= \frac{kT}{\mu_0 m_p}$

human body. To fulfill the full function of an artificial kidney and to improve the quality of life of HD patients have become today's hot research topic [11,12]. Some research work in this field was performed using bioengineered kidneys that mimic a real kidney, as shown recently in Jeremy's exciting report on an artificial seeded rat kidney [13]. These kinds of studies are focused on kidney regeneration and transplantation, together with the possibility of immune rejection. Thus, another way to biochemically clean the waste and recover the lost

Table 1
Variations of essential amino-acids inside human blood before and after HD [10] (unit: μmol/L).

Amino-acid	Before hemodialysis	After hemodialysis	Percentage dropped
Threonine	158.5 ± 45.7	78.6 ± 22.5	50%
Valine	146.2 ± 51.1	118.8 ± 42.1	18%
Methionine	43.6 ± 9.4	33.6 ± 9.1	23%
Isoleucine	42.0 ± 10.2	32.4 ± 9.3	23%
Leucine	107.0 ± 14.1	61.8 ± 11.7	42%
Phenylalanine	112.7 ± 34.4	93.9 ± 26.5	17%
Lysine	123.3 ± 24.6	93.0 ± 22.7	25%
Tryptophan	10.0 ± 2.1	6.0 ± 3.1	40%

nutritional substances from HD therapy becomes one of our current research topics. As schematically shown in Fig. 2, an adsorption device is attached in a way that it allows the dialysate solution to pass through it. The waste molecules are chemically and selectively adsorbed by micro particles inside the device. The nutrient molecules can also be retained by the same mechanism. Thereafter, nutritional substances can be chemically released and infused back to blood. We call this additional process "biochemical waste clearance and re-absorption" because it mechanically mimics re-absorption function of nephridial tubule.

Finding highly efficient adsorbent materials and their working methods also becomes part of our research. And this sort of materials should be easily controllable, thus, it can be trapped in their adsorption area. Because magnetic micron or nano materials can be well controlled under a magnetic field, they become our number one choice as the transport vessel of adsorption materials. Previously, their applications were successfully implemented in a variety of fields, such as: 1) magnetic fluid sealing [14–16], grinding[17], and lubricating; 2) magnetic flaw inspection; 3) oil or water purification [18,19]; 4) modified filling materials; and 5) bio-medical materials, such as MRI image enhancer, magnetic carriers (used in the protein separation process[20,21]), and magnetic medicine (used in targeting process[22–29]). Their usage in the medical field is more intensively investigated in recent years. Chemically combined with adsorption materials, magnetic micro particles provide more opportunities to promote the working efficiency of an adsorption process. In our current researches, chitosan–ferroferric oxide magnetic micro particles are specially used to remove urea from dialysate in the re-absorption process (Fig. 2) during HD; and micro magnetic activated carbon particles are proposed as an adsorbent in the mixed-gas adsorption process. These particles can be moved by magnetic force to a required area, and then be trapped there, working just like normal adsorption materials. Whenever they are saturated for adsorption, they can also be removed from the place by reversing the magnetic force. These two unique properties display the advantages of the magnetic adsorption particles.

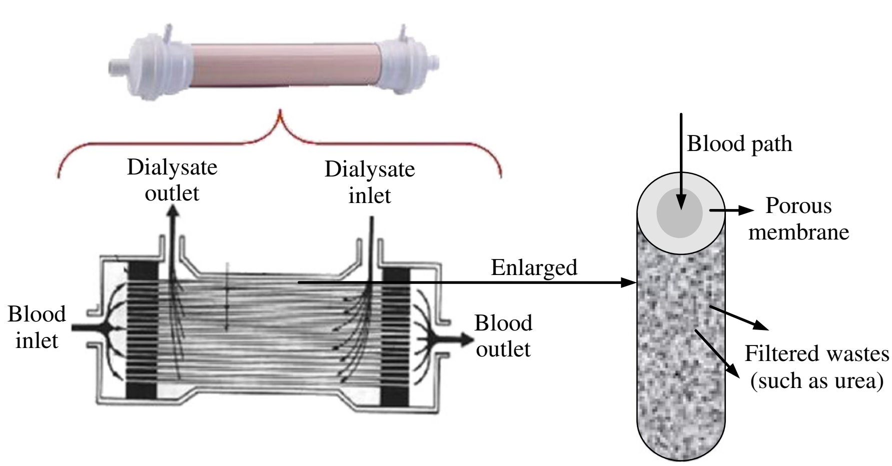

Fig. 1. The organization of a dialyzer.

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