In situ measurements of transport phenomena in sodium bicarbonate cartridges

Anders Arkell

Department of Chemical Engineering, Lund Institute of Technology
In cooperation with: Materials and Chemistry, R&D, Gambro Lundia AB
December 2009

Abstract

In a dialysis machine bicarbonate is added in form of a dry powder in a cartridge. This cartridge is by the machine filled up with water and concentrate is pumped out. Concentration fluctuations due to channelling in the packed salt bed have been investigated.
Temperature and flow are critical parameters and an optima of the temperature of the feed water was found around 24 °C. A higher flow rate has also shown beneficial impact on the system. This leads to two different suggestions of improvements; one involving the dialysis machine and one involving redesigning the cartridge.

Introduction

Hemodialysis is a way to treat patients with acute or chronic renal failure. This is done by passing the patients blood on one side of a membrane and dialysis fluid on the other side. The gradients that the salt concentrations give rise to over the membrane will cause transfer of salts from the blood to the dialysis flow and vise versa. In this way the blood becomes cleaned from nitrogenous waste products and some salts are added to the blood to reset the salt balance.
One of the salts that are used in dialysis is sodium hydrogen carbonate (bicarbonate) and this can both be added to the machine in form of a concentrate on a can or a dry powder in a cartridge. The cartridges have taken over more and more due to the fact that they are easier to handle and that no microorganisms can start to grow in dry powder.
However the cartridge with bicarbonate (BiCart®) experiences fluctuations of the concentration out from the cartridge and this is unwanted.
These concentration fluctuations have been investigated in the present work.

BiCart® cartridges in dialysis

When the BiCart® cartridge is attached to the dialysis machine, the machine first evacuates the air in the cartridge before water enters from the top and fills it up. When it has become filled with water the concentrate pump, downstream the cartridge, starts to pump concentrate from the cartridge. The flow is dependent on the settings on the machine, but a “normal” flow is about 15 ml/min.
Small fluctuations in the concentration out from the cartridge is compensated by the concentrate pump that increase or decreases the speed to make the mass flow out from the cartridge constant. However, if the concentration of the concentrate differs too much from the theoretical value the machine goes into bypass mode and starts its alarm.
This is very irritating both for the patients and the nurses on the clinics. It is also time consuming, because a nurse has to fix the problem before the dialysis machine can go back to normal dialysis mode.
The reason why these large concentration fluctuations occur is channelling in the bed.

The channelling phenomena

Two major phenomena are causing the conditions that allow channels to grow.
The dissolution reaction for bicarbonate is endothermic, which means that the tempered water that enters the cartridge will decrease in temperature when the salt is dissolved. This cause the cartridge to become colder in the bottom than in the top. Because the solubility is temperature dependent [1] (the saturation concentration decreases with decreasing temperature), the salt will thus dissolve in the top of the BiCart® cartridge and recrystallize in the bottom. Heat transfer to/from the surroundings will also have an affect.
Besides this Ostwald ripening is also influencing the system. The Ostwald ripening theory describes that if there are a couple of soluble particles in a saturated solution the bigger particles will grow and the smaller disappear in

order to minimize the energy in the system [2]. When there is a flow in the system the smaller particles will dissolve upstream and the bigger will grow downstream.

In the present case the particles are not individual but in a packed bed and therefore the energy is minimized when recrystallization is present between the particles. This causes the bed to sinter.

The system is unstable, if more salt is dissolved in one place the water flow will increase there due to the reduced resistance. When the flow is increased the dissolution will be locally enhanced which cause the development of a channel. If the powder in the bed is free flowing the channel will almost immediately collapse, but if it has become sintered it can not and then the channel may propagate trough the whole bed. When the channel has grown trough the whole bed water will go through the channel and not become saturated.

Test rig

To investigate channelling and which parameters that affect it, a test rig was built. The tests could not be done on a dialysis machine due to the fact that for example pressure drop over the cartridge can not be measured on a machine and the operating window is too small. More freedom in the tests is reached with a test rig. This rig was custom made for the present study. First there was a heating/cooling bath where a bottle with purified water was placed. This was connected to a circulation loop with a pump and an orifice to adjust the pressure in-between these. A pressure sensor was inserted there to measure the pressure and give feedback to the pump control. The connection to the holder for the BiCart® cartridge was also there. Downstream the BiCart® cartridge a new pressure sensor was placed to measure the pressure drop over the cartridge. After the pressure sensor, but before the concentrate pump, a conductivity meter and thermometer was placed to measure the concentration. Finally the concentrate ends up in a bottle placed on a balance to measure the weight and thereby indirectly the flow.

The cartridge was prepared with nine thermocouples to measure the temperature profile inside the cartridge. These were placed axially in the centre of the cartridge.

Test conditions

The tests that have been done have been performed under varying conditions with respect to the temperature of the feed water and the flow rate. The temperature of the feed water was tested for 16, 24, 30 and 37 °C and the flow rate was tested for 10, 15, 20, 25 and 30 ml/min.

Visualization of the channeling

Channelling could easily be seen in the results from the tests.

The concentration directly indicates if there is any problem. As seen in figure 1 the concentration is fluctuating at the end of the test and two important times is marked with arrows. The red arrow is where the concentration fluctuation starts and the yellow arrow where the concentration reaches a temporary top before the cartridge is empty.

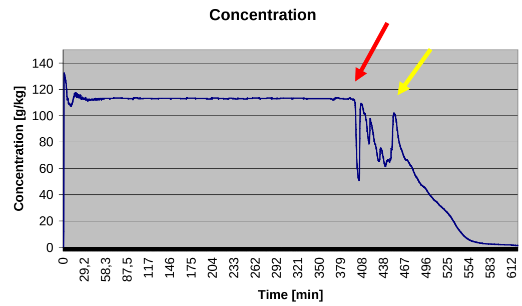

Figure 1. Concentration in the case of a flow rate of 15 ml/min and an inlet temperature of 37 °C. Red arrow: channelling onset, yellow arrow: temporary rehomogenization of powder bed.

This will be compared with the pressure drop over the cartridge, see figure 2. The arrows are pointing out the same times as in previous graph. As seen, the pressure drop decreases when the concentration decrease and vice versa. This is because a channel has grown through the bed. The channel causes the concentration to decrease but also the pressure drop as the channel is much easier to pass than the bed.

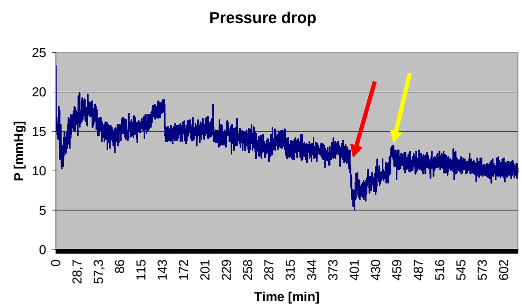

Figure 2. Pressure drop for a test at an inlet temperature of 37 °C and a flow rate of 15 ml/min. Red arrow: channelling onset, yellow arrow: temporary rehomogenization of powder bed.

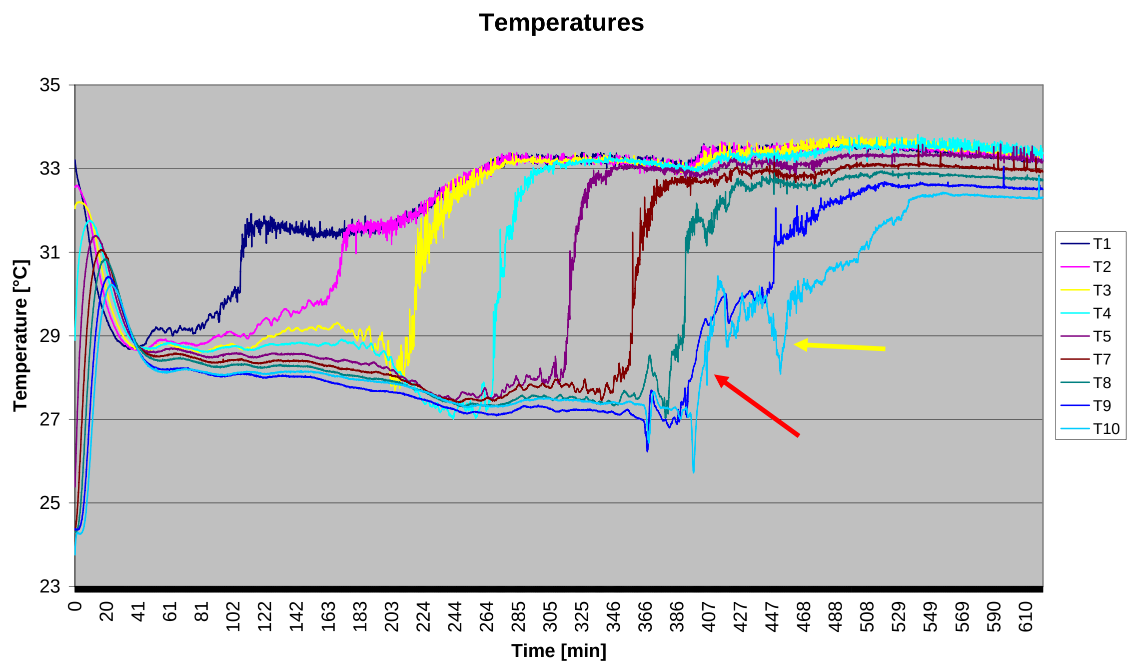

Figure 3. Temperature profile for a test at a flow rate of 15 ml/min and a temperature of 37 °C. Red arrow: channelling onset, yellow arrow: temporary rehomogenization of powder bed.

The temperature profile for the same test is seen in figure 3. The red arrow is pointing at an increase in temperature and the yellow one at a decrease. The explanation to this behaviour is that when a channel starts to grow the main water flow will flow through it instead of the bed and therefore warm water will flow by the thermocouples end the temperature will raise. When the concentration increases, and thus also the pressure drop, this is because the channel has partly and temporary collapsed and then the temperature decrease as the channel is not present anymore.

Method evaluation

These three methods are complementing each other in a good way. For example the pressure drop does not always catch the channelling, but the temperature profile always does. Another even greater benefit is that the concentration does only decrease if the channel has grown through the whole bed, but the other two methods also measure small channels.

So why is it of interests to see a channel that have not gone through the whole bed and thereby not caused any fluctuations? Well, although the channel did not grow through the whole bed in the actual test it may penetrate the bed next time. This means that the two methods by measuring the pressure drop and the temperature profile give insight into the process inside the cartridge.

Results & Discussion

If the different tests are compared in respect to significant channelling in the concentration curve the results from this is as seen in table 1.

Table 1. The number of tests that has showed channelling.

	37 °C	30 °C	24 °C	16 °C
10 ml/min	3/4	1/4	0/3	0/1
15 ml/min	3/4	0/4	0/3	0/1
20 ml/min	1/4	0/4	0/3	0/1
25 ml/min	0/4	0/4	0/3	0/1
30 ml/min	0/4	0/4	0/3	0/1

As seen, the increasing flow is affecting the channelling significantly. No matter what temperature the test has been done at, the results become better for higher flow rates.

The reason why higher flow rates is better is most likely because the higher flow will cause a higher force on the bed. This force, if it is big enough, can break down the sintered powder causing it to fall down in the hole if a channel has started to grow.

However this has limits: Previous work [3] had shown that flow rates about 100 ml/min will cause channelling again. This is probably because very high flow may result in “drilling” trough the bed.

It is clear that lower temperature is better than 37 °C in respect to the channelling problem. What is not seen in table 1 is that the concentration curve shows tailing in the end especially for 16 °C but

also for some of the tests at 24 °C. This is not a wanted effect because if the concentration falls before the cartridge is empty a lot of salt will be left unused.
The reason to this tailing is because the solubility kinetic is to slow at low temperatures and the water has not enough time to get saturated when the bed becomes shorter.
If this is taken into account a temperature optimum around 24 °C is found.

This has shown two ways to archive a more stable concentrate out from the cartridge in respect to concentration. However, the flow rate can not be changed without affecting the treatment of the patient. Yet the variable that is of interest is not the flow rate, but the linear velocity. These are related to each other by equation (1) seen below.

$$\bar{v} = \frac{\dot{Q}}{A} \qquad (1)$$

When the $\bar{v}$ is the linear velocity, $\dot{Q}$ the flow rate and A is the cross-section area of the cartridge. By changing the cross-section area the linear velocity can be changed.

Future work
This work has been done in a test rig and to evaluate the results the solutions must be tested on a dialysis machine that operates under real conditions.

For the case of higher velocity inside the cartridge the cross-section area can be decreased as already been described. But if the area is decreased the volume of the cartridge will also decrease and this is not a solution. However the channels occur in the bottom of the cartridge and therefore the area must be decreased there. In the top it can on the other hand be increased so that the volume of the cartridge is kept constant.
To test this, a new cartridge must be drawn, printed out on a 3D printer and tested. The tests must be statistically evaluated with standard BiCart® cartridges as references.

For the case of lower temperature on the feed water to the BiCart® cartridge some kind of process change must be done. The simplest is to put in a heat exchanger in the machine that heat exchanges the feed water to the BiCart® cartridge with the feed water to the heating vessel. This is seen in figure 4.

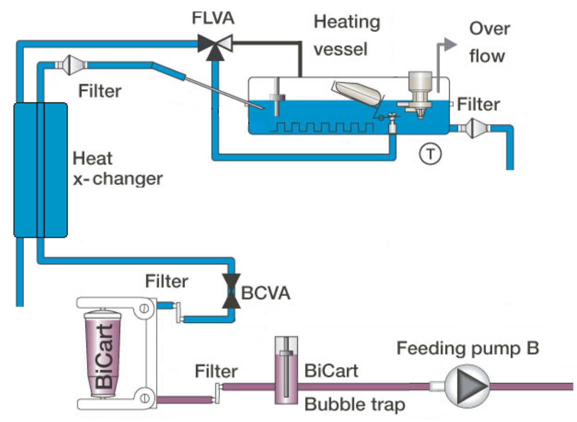

Figure 4. Suggestion for reducing channelling. A heat exchanger may be implemented to decrease the temperature of the water to the BiCart® cartridge.

Because the flow to the BiCart® cartridge is small (about 15 ml/min) in comparison to the main flow (about 500 ml/min) the heat exchanger can be quite small. This is beneficial because then there is very likely enough space in the machine to insert it without having to do a redesign of the machine.
The low bicarbonate concentrate flow also means that the concentrate does not need any heating before it enters the dialysate main flow.

Conclusions
The new way by studying the system, in respect to the pressure drop and the temperature profile inside the cartridge, has shown to be very useful in order to get an insight to the process inside the cartridge walls. This has given information that is not possible to acquire on a dialysis machine.
The test rig also gave the opportunity to change the flow and the temperature outside the limits of the dialysis machine. This gave the possibility to study the behaviour over a wider range of parameter settings which gave a lot of information about the system.
The present work resulted in two suggestions for reducing channelling. By decreasing the temperature of the feed water flow or by reshaping the cartridge so that the cross-section area is redistributed and the water velocity increases at the bottom of the cartridge.

References
[1] Green, D. W. and Perry, R. H., Perry's Chemical Engineer's Handbook, 8th edition, 2008, McGraw-Hill Companies Inc., China
[2] H. Wennerström, personal communication, September 2009, Lund, Sweden
[3] G.-I. Bertinsson, personal communication, October 2009, Gambro Lundia AB, Lund, Sweden