A study of the mass transfer of dissolved oxygen into gaseous phase in a deaeration system

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12th of January 2012

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Abstract

During milk and beverage processing, oxygen dissolves into the product and the product quality is decreased because of aroma losses and shortening shelf-life. To overcome this problem the product has to pass a deaerator, which decreases the oxygen concentration significantly. In this study the main objective was to examine different mechanisms that affect the mass transport of dissolved oxygen into gaseous phase. Most of the oxygen is removed initially, while the rest is removed during the diffusion part which happens in the end of the pipe. The diffusion mechanism is assumed to follow a differential equation of first order, where the void, bubble size and velocity seem to play an important role. The pattern of the flow in the pipe doesn't look like what was expected, and has a tendency to stratify along the pipe. This results in very high liquid velocities which affects the time of diffusion negatively. High ΔP over the valve gives a more splashy flow pattern while low ΔP gives a more distinct stratified flow. From the void measurements it is found that high ΔP gives higher void, which could be explained by the increased opportunity of nucleation, thus to form bubbles. Increased void results in higher mass transfer contact area between the bubbles and the liquid, but in the same way the liquid velocity increases.

Introduction

Dairy and beverage products always contain a certain amount of air in various forms. There are mainly two different forms in which the air can be fixed into the product. Its either dissolved air or dispersed air. The first one is dependent of the temperature and regulated by Henry´s law which says that the dissolving effect increases when decreasing the temperature. Dispersed air in the product becomes present primarily when the temperature rises and bubbles are created. Due to Stokes law these bubbles will rise to the surface and burst,
but if the bubbles are small enough they will spread homogenously in the product.

When the milk is taken from the cow´s udder it contains about 4.5-6 % by volume. During the transport from the farmhouse to the diary plant the milk will get in contact with the atmospheric air, which will increase the air content of the milk. When the raw milk is waiting on the refinement it´s stored at low temperatures, in order to limit the growth of bacteria, which will increase the amount of dissolved air. At the diary factory it is not unusual with an air content of 10 % by volume.

The air, especially the dispersed one, can cause several of problems, both process and product related. The process problems include fouling in the pasteurizer, cavitations in the homogenizer and reduced

skimming effect in the separator, while the products problems include shorten shelf-life and product-and aroma losses.
Beverages, for example juices, the problems are mainly related to the product quality. The present oxygen in the air causes degradation of the c-vitamin and furthermore strong undesired flavors and discoloration may occur. For juice the normal acceptable O_2 content is 0.5-1 mg/kg, while the limit for dairy products is a bit higher, around 2ppm. [Bylund, 2003]

Theory

The current deaeration process (see fig.1) is based on a vacuum technique, which means that the product is passing a throttle valve where a pressure drop occurs. During this time the product becomes oversaturated by air, and air bubbles start to grow due nucleation and cavitation.
Along the pipe, the air in the product will be transported into the bubbles due diffusion.
The last phenomena are the one that is going to be studied in this thesis.
When referring to air, only oxygen will be considered as it is the component that causes the products problems. As the system is turbulent, the diffusion is assumed to be convective and not molecular. The bulk concentration of oxygen in the liquid product will decrease by time along the pipe and is described by following differential equation:

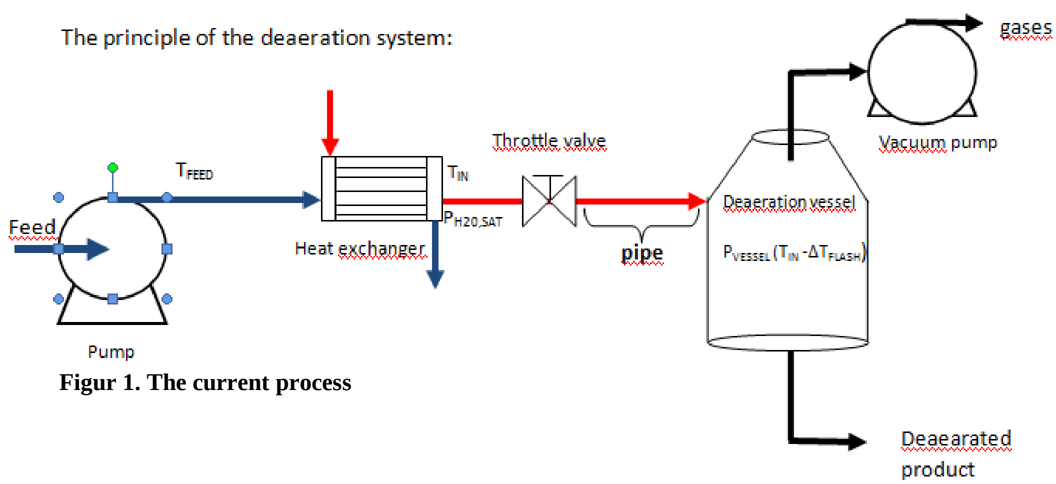
$$\frac{dc_{bulk}}{dt} = k_M \cdot a \cdot \left(c_i - c_{bulk,t}\right) \quad \text{eq. 1}$$

Where k_M is the mass transfer coefficient, a the specific contact area between the gas phase and liquid phase, and c_i the interfacial concentration in the bubble.

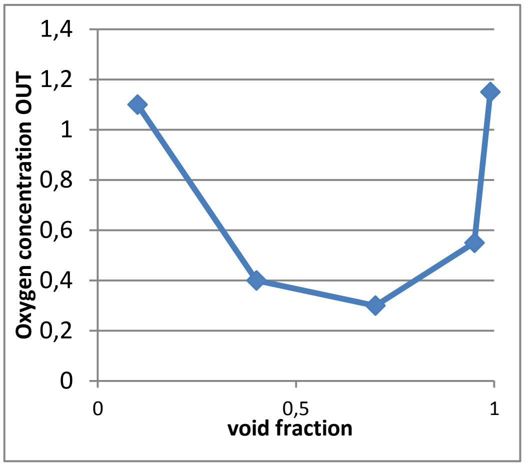
$$k_M = \frac{Sh \cdot D}{d_p} \qquad \text{[Singh, 2003]} \qquad \text{eq.2}$$

$$a = \frac{6 \cdot void}{d_{mean}} \qquad \text{[Lidén, 2010]} \qquad \text{eq.3}$$

where the void is the volumetric gas fraction in the system, d_{mean} the mean diameter of the bubbles, Sh the Sherwood number and D the diffusion coefficient. The void fraction is very important to understand as it also decides the velocity of the liquid in the system. High gas fraction means less cross section area to flow through, thus high velocity. High velocity means less time in the pipe, thus less time for diffusion to happen. The bubble diameter affects the two parameters in both directions as well.
To understand how the parameters in eq.2 and eq.3 affect the complex system, a simulation of the eq.1 was done in Matlab.
When the void fraction was varied and all other parameters were kept constant, following behavior of the outgoing oxygen concentration in the liquid was obtained, see fig 2.

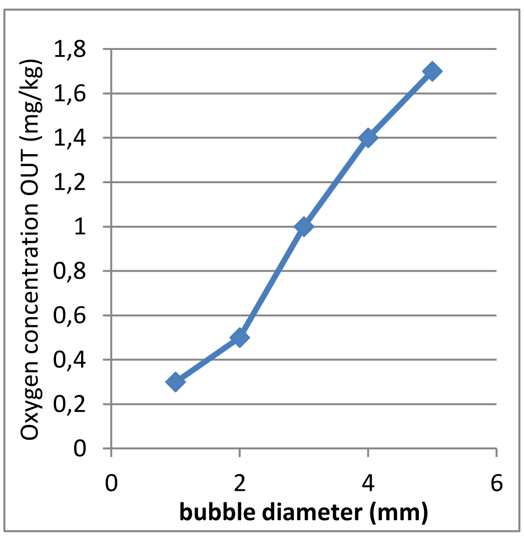


Figur 1. The current process



Figur 2. Outgoing oxygen concentration at different void fractions.

It is clear that the oxygen removal in the process is favored by a void fraction in the span of about 40-90 %. Lower or higher void than that decreases the efficiency dramatically. When varying the bubble diameter following result of the oxygen concentration was obtained, fig 3.



Figur 3. Outgoing oxygen concentration at different bubble diameters.

The oxygen removal is favoured by small bubble diameter as it increases the value of k_M. The value of the specific area does not decrease enough to overcompensate the increasing k_M.

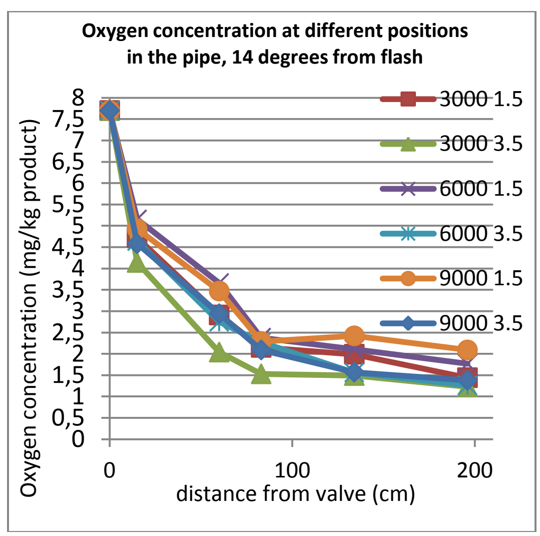
Materials and Methods:

Four parameters were studied along the pipe: oxygen concentration, pressure profile, visual analyze and void fraction profile. By changing the position of the pressure gauge and oxygen sensor along the pipe, the two first parameters were extracted by logging the data into Labview. The visual analyze were done by using a transparent pipe in Plexiglas and taking photos at different positions along the pipe. The void fraction was measured by a special-designed sensor which analyzes the capacitance of the medium running inside the pipe. During the experiments the liquid flow rate was changed to 3000, 6000 and 9000 l/h. The pressure drop (ΔP) over the throttle valve was either 1.5 or 3.5 bar. The temperature of the liquid was set to 18 degrees and the pressure in the vessel corresponds to a negative flash of 14 degrees. The liquid is with other words 14 degrees from boiling. The length of the pipe was about 2 meters.

Results and Discussion

Oxygen profile:

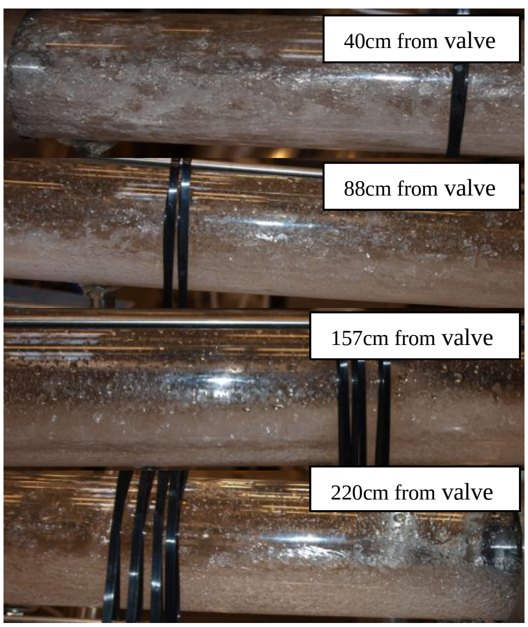
The results from the oxygen measurements are shown in fig 4.



Figur 4. Oxygen concentration along the pipe

It was observed that the oxygen concentration decreased more in the beginning of the pipe than in the end. The initial part represents the nucleation and diffusion combined and the small slope in the end represents the diffusion part. Low flow and high ΔP consequently gives lower outgoing oxygen concentration, while high flow and low ΔP gives higher outgoing oxygen concentration. The main part of the oxygen removal takes part during the initial part which happens relatively instant during the ΔP over the valve. It is therefore logic to assume that it's mainly diffusion in the end, as no ΔP occurs there.

Visual observations along the pipe:
From the pictures taken it was observed that the flow stratifies along the pipe, with a splashy jet in the beginning and a smooth liquid film at the end, see fig 5.

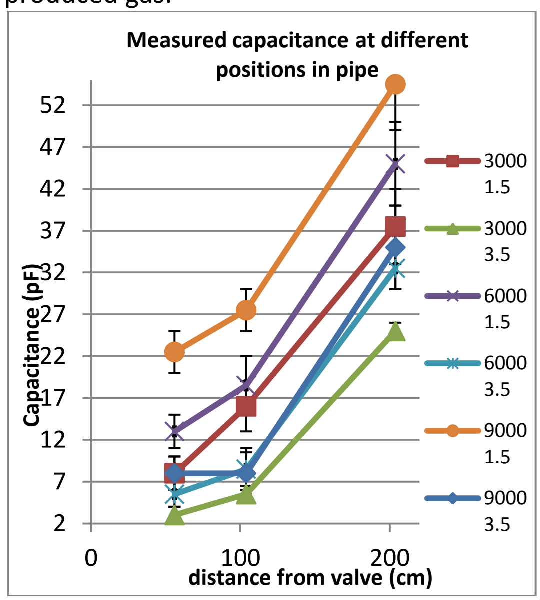


Figur 5. 3000l/h ΔP:1.5 bar.

It is obvious that the pipe is only partially filled by water. For ΔP: 3.5, the flow is much more turbulent and the pipe is filled by a splashy jet, even at the last position, see fig 6. It is apparent that low ΔP results in a much more stratified flow along the pipe.

Figur 6. 3000l/h ΔP:3.5 bar.

Void fraction
The void is measured with the capacitance measurement method. The plot of the measured capacitances, see fig 7, for each flow/ΔP indicates that the capacitance increases when moving the sensor closer the vessel. It is also a significant difference between the ΔP. 1.5 in ΔP results in higher capacitance than for 3.5. Low capacitance means high void which should be reasonable because high ΔP means larger oxygen removal and thereby more produced gas.



Figur 7. 3000l/h ΔP:1.5 bar.

The void extracted from the capacitance method, is reaching its maximum level at position 60 cm. and decreasing closer the valve. This results in a decreased velocity. High ΔP gives higher void than low ΔP and therefore higher velocities. It has to be taken account that the capacitance sensor is NOT calibrated for different flow patterns but only for the two edge points, pure water and pure air.

Conclusions

The oxygen concentration in the pipe decreases due two phenomena: nucleation and diffusion. The first part stands for about 75% of the oxygen removal while the diffusion stands for 25 %. High ΔP over the valve gives better oxygen removal and better diffusion efficiency than low ΔP. The total oxygen removal is favoured by low flow since it increases the holdup time in the pipe.

The flow pattern in the pipe varies tremendously: from a splashy jet flow to a smooth stratified flow. In the beginning of the pipe, the liquid is wetting the whole periphery, and in the end of the pipe, the liquid is in the bottom while the gas is in the top. The liquid in the bottom consists of a two-phase system including both water and gases. Because of all the present void, the liquid has to travel throw a smaller cross section, which results in a higher velocity.

The void in the system according to the model is crucial for the mass transport as it determines two very important parameters: velocity and specific surface area. High void is benefiting the specific surface area to a certain maximum, but it also increases the velocity of the liquid. Low velocity and high void is obviously the optimal situation. The measured void are in the order of 80-99% which is much more than expected. It results in very high velocities. High ΔP gives higher void than low ΔP.

References

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