Separation of air bubbles from milk in a deaeration process

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May 2012

Abstract

Dissolved oxygen is a problem in the dairy industry and is necessary to get rid of. It decreases the shelf-store time and impair the process performance. In this work, a new technique to deaerate dairy products has been investigated. The new technique is based on nucleation of air bubbles caused by a rapid pressure drop, and then separation of these in a vacuum vessel. Previous work has shown good results, and understanding of the behavior, for water, but for dairy products, the separation of bubbles has not worked. The focus in this work has been on understanding the different mechanisms of the process when deaerating water and dairy products respectively. Additionally the goal was to get successful deaeration results on milk and orange juice. The work has shown a great difference in the size of the created bubbles in water and products, which is the key to the aberrantly results. The mean bubble size in milk was measured to 100 µm (roughly a tenth of the bubble size in water), and the size was not significantly affected by different temperatures and pressure drops. The most critical process parameter for the oxygen transfer into bubbles was found to be the temperature (degrees from flash). The pressure drop had no impact on the result on product, which it has on water. Two designs of the vacuum vessel was investigated, one vertical and one horizontal alignment. It was shown that the separation of the bubbles do not work in the vertical vessel since the flow conditions was very unbeneficial for the small bubbles to rise in. In a horizontal alignment though, the deaeration reached final oxygen levels < 1 ppm at a low capacity.

Keywords: deaeration, dairy process, milk, bubbles, turbulent dispersion

Introduction

Milk is not just a drink - it´s a bulk chemical, being the raw material to a large number of dairy products. It is processed in many different ways to get products with desired quality, why there are many unit operations in the dairy factory, all optimized for its duty. Since the dairy industry is very big, and the costumers demand cheap but high quality food, every improvement is worth a lot.

Naturally milk contains about 8 ppm oxygen which is desired to be decreased to 1 ppm.

Deaeration is a necessary process in the diary and beverage industry due to many reasons. It is applied on milk as well as juices and carbonated beverages to improve quality and storage time, but also to improve the processing performance. [Bylund 1995]

The conventional deaeration process is built on the mechanism of flash boiling. This means that the feed enters a vacuum vessel at a temperature higher than the current boiling temperature. The solubility of oxygen approaches zero and the dissolved gases will be rejected from the liquid.

In ”The new deaeration concept” the mechanism is to create gas bubbles with a rapid pressure drop over a pressure relief valve. The created bubbles are then separated from the liquid in a vacuum vessel (with temperature below the boiling temperature), and the deaeration is done without adding energy in the form of heat.

The aim of this project was to answer two questions:

***Why** does the process not work on products?*
***How** can it be modified to work on products?*

Theory

The separation of the bubbles is done by gravity by letting them rise to the surface. The movement of the bubbles is described by using a laminar model, *Stoke's law*.

Stoke's law gives the rising velocity of a bubble according to:

$$v_{stoke} = \frac{dh}{dt} = \frac{2}{9} * \frac{gr^2(\rho_f - \rho_p)}{\mu}$$

[Bylund 1995]

The bubble radius is depending on the surface tension according to *Laplace's* equation:

$$P_{in} - P_{out} = \frac{2\gamma}{r}$$

Where $P_{in} = \frac{\sum_i n_i RT}{V_{bubble}}$

The amount of gas in the bubble is depending on the mass transfer according to:

$$\frac{dn}{dt} = K_l a_{bubble}(C_i - C_b)$$

The disadvantages with this model are that it assumes an ideal and direct rising to the surface without disturbances from turbulence.

A more sophisticated model is the turbulent dispersive model.

The turbulent dispersive model also includes a turbulent term which causes a mixing effect on the bubbles, besides the convective rising velocity. The model is generally written as:

$$\frac{dc}{dt} = -v_{stoke}\frac{\partial c}{\partial x} + D\frac{\partial^2 c}{\partial x^2}$$

[Skoglund, 2007]

The disperison coefficient is calculated using a correlation by *Roberts et al:*

$$D = D_m u^*$$
$$u^* = 3{,}1n * u_{hydraulic} R_h^{-1/6}$$

The boundary condition is set to a *Dirichlet condition* at the bottom:

$$c(x = 0) = 0$$

Since the flux or the concentration is unknown at the liquid surface, the simulation is done for an “infinite” discretzation domain. The simulation is done for a distance ten times longer than the real depth, but only the first tenth is of interest. The second boundary condition is also set to a *Dirichlet condition*, assuming the concentration to be zero at the last discretization point:

$$c(x = 10h) = 0$$

The turbulent-dispersive model has the disadvantage that is does not take care of flow disturbances.

Method

The size of the created bubbles in milk was an unknown but very important parameter. The bubble size is essential for the separation, in consideration of the rising velocity, but also of the fact that small bubbles are more sensitive for turbulence than bigger ones. It was therefore necessary to measure the size of the bubbles. The bubbles were measured by leading a small part of the product after the pressure relief valve into a thin capillary. The capillary was photographed and the bubbles were able to be distinguished and measured.
The process parameters degrees from flash point, and pressure drop over the valve were investigated to see the effect they had on bubble size and oxygen removal.

As seen in Figure 1, the oxygen levels were measured at four positions in the process: at the feed inlet, after the pressure throttle, after the vacuum vessel and in the product outlet.

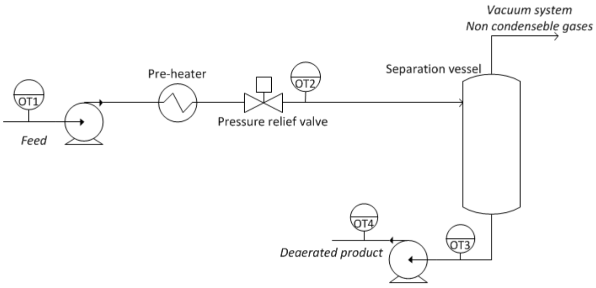

Figure 1 Schematical flowsheet of a deaeration process with oxygen sensors marked out.

The oxygen removal was investigated in two different designs of the vacuum vessel; one vertically oriented, and one horizontally oriented. In the vertical vessel, the bubble-containing product enters the vessel above the liquid surface and leaves it in the bottom. In the horizontal vessel the feed enters the vessel from the side, and leaves it at the opposite side. Drawings of the vessels are presented in Figure 2.

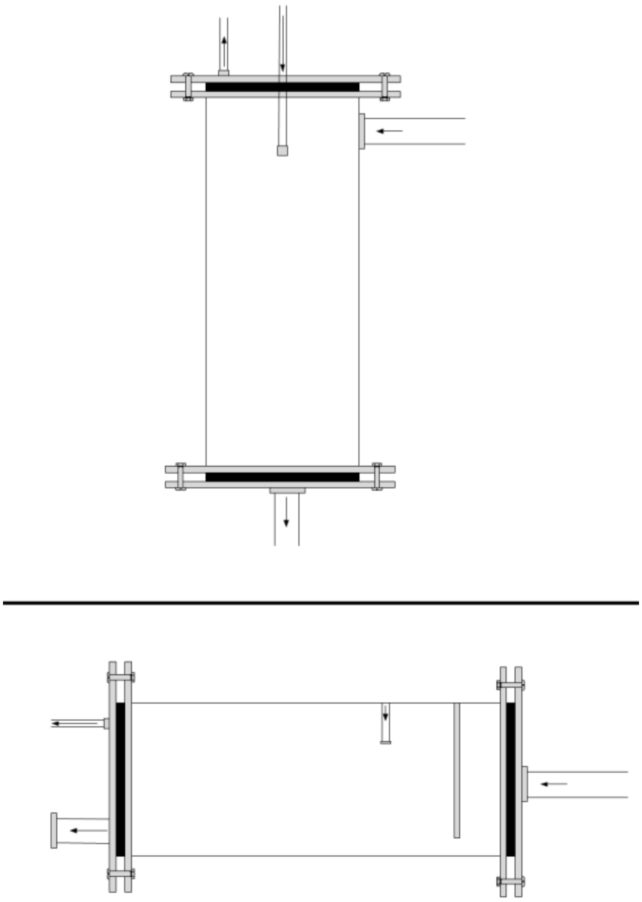

Figure 2 Schematical drawings of the two deaeration vessels.

The oxygen levels were used to calculate the performance of the process in terms of nucleation efficiency (E_N), bubble separation efficiency (E_{BS}), and the total efficiency (E). This was a convenient way to compare different experiments, see Figure 3 for definition.

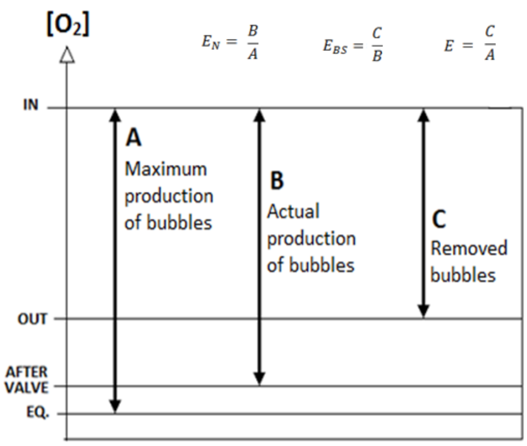

Figure 3 Picture of the separation efficiencies.

In the horizontal vessel, the deaeration results are referred to the *relative hold up time*:

$$RHT = \frac{hydraulic\ space\ time}{stokes\ rise\ time} = \frac{\frac{L}{u_{hydraulic}}}{\frac{H_m}{v_{stoke}}}$$

The bubble separation efficiency (E_{BS}) is given by:

$$E_{BS} = \frac{C_{O2}^{inlet} - C_{O2}^{outlet}}{C_{O2}^{inlet} - C_{O2}^{after\ valve}}$$

The E_{BS} vs. RST graph gives indications on how much the dispersion slows down the separation compared to an ideal Stoke's law rising. These results were complemented with simulations of the turbulent dispersive model. The PDE was solved with the *Finite Volume Method* in *MATLAB*.

Results

Variation of the process parameters degrees from flash and pressure drop over the valve gave results presented in Table 1. At the same time the bubble sizes were measured. The conclusion was that the size did not have any significant connection to the process conditions. The mean value of the bubble diameter in milk was measured to 100 µm.

Table 1, results on the oxygen removal after the pressure throttle at different degrees from flash and pressure drops. The flow rate was 1500 l/h and the pressure in the vacuum vessel was 0.158 bar.

OT2 [ppm]		**Degrees from flash [°C]**		
		-5	**-2**	**+2**
Pressure drop [bar]	**1.2**	0.64	0.45	0.37
	2.0	0.60	0.48	0.37
	2.8	0.61	0.50	0.39

The deaeration (with horizontal vessel) results for the flows 750 l/h and 1000 l/h were plotted as oxygen profiles and as E_{BS} vs. RHT for different liquid levels in the vessel. The results are presented in Figure 4 and Figure 5.

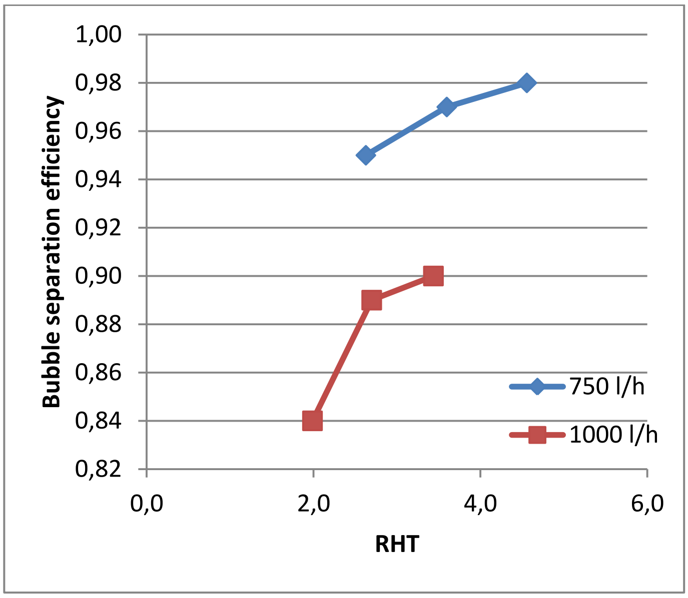

Figure 4, deaeration results in the horizontal vessel for 750 l/h and 1000 l/h.

The oxygen profile in the process is showed in Figure 5 for the flows 750 l/h and 1000 l/h respectively. The liquid level in the vessel is 6 cm which corresponds to hydraulic space times of 85 and 62 seconds.

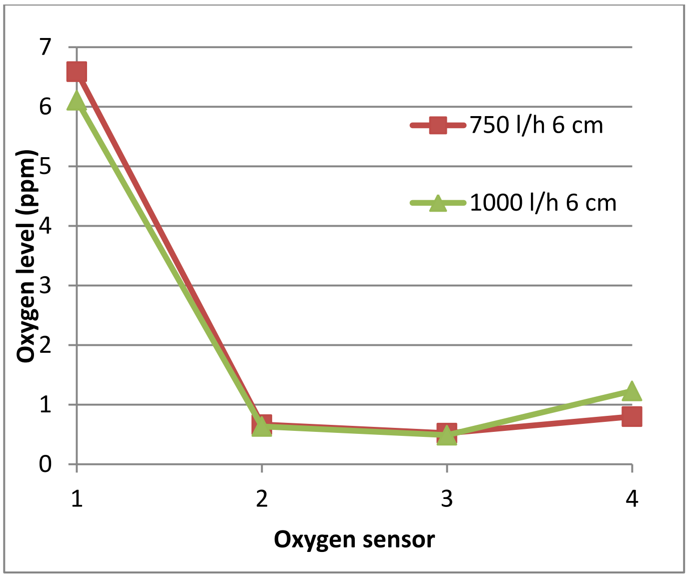

Figure 5, oxygen profile in the horizontal deaeration vessel for two flow rates at the same liquid level.

The turbulent diepsrsive model was solved for the same flow and liquid level as in the experimental results. The results are plotted together as E_{BS} against the relative hold up time in Figure 6.

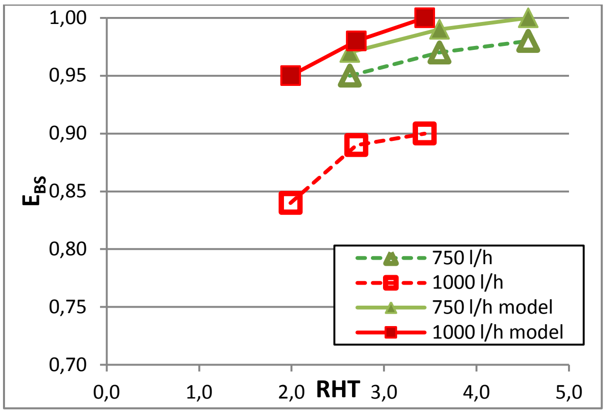

Figure 6 Results of E_{BS} vs. RHT for the turbulent dispersive model and the experimental results.

Discussion

The results in this work showed a significant difference in the transfer of oxygen into bubbles for product and water respectively. The milk contains many colloidal particles leading to another mechanism for creating bubbles than in water. In milk, the nucleation tends to be of a heterogeneous type, in contrast to water which nucleates mainly in a homogeneous manner. That the nucleation occurs easily in milk leads to a big amount of bubbles, and a big surface area for mass transfer, why the bubbles stay small. The small bubbles are hard to separate from the liquid, and the experimental results showed high requirements on the space time and the flow pattern. When the deaeration vessel was tilted, the result showed that big flow disturbances caused by a “plop effect” were eliminated. Also the convective flow in the vessel changed from opposite the rising direction, to a perpendicular direction.

The experiments with the horizontal vessel showed that E_{BS}-values of 0.95 could be reached at 750 l/h. At the providing conditions this corresponded to an outlet oxygen level <1 ppm which fulfils the requirements. With a 33% higher flow, 1000 l/h, the E_{BS} and outlet oxygen level showed a slightly worse result. The explanation is that the flow pattern was another with a lot more disturbing eddies caused by turbulence.

The computational simulations with the turbulent-dispersive model showed good fit to experimental data at 750 l/h. The model does not take care of the flow disturbances which, according to the experimental results, reduces the bubble separation efficiency. For a flow of 1000 l/h the model does not correspond well to experimental data due to that. This concludes that the turbulent dispersion model is appropriate for this problem but improvements that take care of flow disturbances are required.

Conclusions

Nucleation in milk and juice is not depending on the pressure drop over the relief valve, unlike water. The critical parameter on the mass transfer into gas bubbles is the degrees from the flash temperature.

The created bubbles in milk are small, in average 100 µm in diameter and the size has no significant dependence on the pressure drop or the degrees from flash. The size of the created bubbles is the critical parameter for the separation. The small bubbles get a very small rising velocity in the separation vessel and demands high space times. They are also more sensitive to the flow pattern than the bigger bubbles are.

The vertical separation vessel is not applicable for deaeration of milk since the rising distance for the bubbles is too large, the flow pattern is unbeneficial, and the convective flow is opposite to the rising direction. Deaeration to oxygen levels <1 ppm could be reached in a horizontally aligned separation vessel at rather low capacities.

Nomenclature

a_{bubble}	Area of a bubble	m^2
E_{BS}	Bubble separation efficiency	-
c	Concentration	units/m^3
C_b	Concentration in bulk	moles/m^3
C_i	Concentration at interface	moles/m^3
D	Disepersive coefficient	m^2/s
D_m	Mean diameter	M
g	Gravitational constant	m/s^2
H_m	Maximum depth	m
K_l	Mass-transfer coefficient	m/s
L	Length of vessel	M
n	Mannings coefficient	-
n_i	Molar amount of component i	moles
P_{in}	Pressure inside the bubble	Pa
P_{out}	Pressue in bulk	Pa
r	Bubble radius	m
R	General gas law constant	J/K mol
R_h	Hydraulic radius	M
RHT	Relative hold up time	-
u^*	Turbulence velocity	m/s
$u_{hydraulic}$	Hydraulic velocity	m/s
V_{bubble}	Volume of a bubble	m^3
v_{stoke}	Stoke's rising velocity	m/s
γ	Surface tension	N/m
μ	Viscosity	Pa s
ρ_f	Density of fluid	kg/m^3
ρ_p	Density of bubble	kg/m^3

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