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Effect of humidity on dynamic foam stability

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ABSTRACT

It is experimentally shown that the stability of non-overflowing pneumatic foams, such as those used in the Bikerman foam stability test, is strongly dependent upon the gradient of humidity within the freeboard of the column. Growing foams can be prevented from exhibiting collapse, even at surfactant concentrations significantly lower than the critical micelle concentration, by saturating the air above the foam surface thereby preventing liquid evaporation. These observations have important implications for the performance of flotation devices, as well as instruments designed to measure the stability of aqueous foams. Meteorological data for two mining sites in Australia throughout a single year shows the variability of humidity, and therefore stability, of flotation froths.

1. Introduction

It is a common experience of individuals who consume carbonated beverages that, upon dispensing an aliquot of the beverage, the froth or 'head' on the top of the liquid rises rapidly up the glass. Sometimes the froth spills over the rim of the glass, but often it just reaches the lip and then, surprisingly, stops growing at precisely this point. In this paper we will propose that the stability of the froth is governed by the evaporation from the top of the surface which is controlled, *inter alia*, by the humidity (or humidity gradient) above the foam. This observation has implications for the efficacy of common tests of foam stability (or 'foamability') that are used to determine the tenacity of froths in a variety of industries in that the results of all such tests are dependent upon environmental humidity, and this dependency has thus far been largely overlooked.

Whilst performing measurements of bubble size distribution in foam using a nuclear magnetic resonance method (unpublished work within our group) a non-overflowing pneumatic foam was created in a column within the magnetic resonance spectrometer. A non-overflowing pneumatic foam is one that is produced by sparging a gas into a surfactant solution such that it forms an equilibrium height because the rate at which gas is added to the bottom of the froth is equal to the rate at which gas is liberated from the top surface of the foam due to bubble coalescence. Results showed that bubble size distribution was largely independent of the height at which size was probed. This indicated that the height of eventual foam collapse was a result of physical effects occurring at the foam surface rather than internal bubble coalescence within the bulk of the foam. Such physical effects include mechanical disturbance of the froth surface or evaporation, and, because the surface was located within the column, the former was largely precluded. Thus, this preliminary evidence suggested that the equilibrium height that a non-overflowing pneumatic foam can achieve is dependent upon the rate of evaporation from the foam surface. In fact, Tamura et al. (1997) found that when the relative humidity of the surroundings is reduced, the stability of a single, separated foam film decreased. Exowera and Kruglyakov (1997) briefly mentioned early Russian studies that showed that evaporation caused a decrease in foam stability but that there had been no systematic work carried out.

In this paper it will be shown that the stability of a non-overflowing pneumatic foam is dependent upon the gradient of relative humidity in the freeboard of a column, and the implications that this result has upon the stability of other foaming systems will be discussed. (The 'freeboard' is the space between the bed surface and the top of the column in fluidisation, and is used to describe the space between the froth surface and the top of the column herein.) We do not claim that this work is directly representative of practical flotation froths, although there is a precedent in the literature for using descriptions of gas–liquid foams to model mineralised systems (Neethling and Cilliers, 2003). Rather we seek to demonstrate a previously overlooked phenomenon that is likely to have a bearing on stability tests in flotation, as well as having broader relevance to gas–liquid systems; clearly in a flotation froth with total surface coverage there will be no evaporation at all, although such froths are rare. Similar tests on the influence of humidity upon the stability on mineralised froths are the subject of ongoing research.

2. The Bikerman foam stability test

The Bikerman (1938, 1973) foam stability test is perhaps the best-known method of quantifying the tenacity of a foam and has been

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used variously to describe the 'foamability' of systems as diverse as cider (Blanco-Gomis et al., 2009), steel production (Morales et al., 2002) and foaming in desulphurisation operations (Hansen et al., 2008). However, there has recently been a surge of interest in using the method to estimate the performance of froth flotation plant (Barbian et al., 2003, 2005, 2006; Aktas and Cilliers, 2008).

Bikerman (1973) stated that the maximum height that a non-overflowing pneumatic foam can attain, $H_{\max}$, "is, within a range, proportional to the linear gas velocity", j_g (which is know herein as the gas superficial velocity). The advice given as to the appropriate 'range' is to ensure that the "gas velocity is not too small (otherwise evaporation is too upsetting) and not great enough for the blast to rupture the lamellae." Thus the following relationship was proposed:

$$\Sigma = \frac{H_{\max}}{j_g} \tag{1}$$

where Σ is Bikerman's 'unit of foaminess' and has units of time. It is implied in Bikerman's work that, so long as the experiment is carried out within an unspecified range of j_g, Σ is an intrinsic property of the foaming liquid.

It is possible to show that the Bikerman unit of foaminess, Σ, cannot give an intrinsic measurement of the stability of an arbitrary foam created from a specific surfactant solution; the foam stability must be dependent upon the method by which it is made. If one, for the time being, overlooks a potential dependency upon humidity, it is reasonable to assert that $H_{\max}$ is a function of j_g, a representative mean bubble size at the bottom of the foam, r_b, the dynamic viscosity and density of the interstitial fluid, ρ and μ respectively, the surface tension, σ, and the acceleration due to gravity g, i.e.

$$H_{\max} = f(j_g, r_b, \mu, \rho, \sigma, g) \tag{2}$$

The surface tension may appear as an independent variable in its own right, or as a proxy for other surface variables as explained by Stevenson and Galvin (2007). Thus, by Buckingham's (1914) π-Theorem we see that four dimensionless groups are necessary and sufficient to characterise the system. The four groups that satisfy the constraints of the π-Theorem are:

$$\frac{H_{\max}}{r_b} = f\left(\frac{r_b j_g \rho}{\mu}, \frac{\mu j_g}{\rho g r_b^2}, \frac{\mu j_g}{\sigma}\right) \tag{3}$$

where the first group in parentheses is recognised as a Reynolds number, the middle one as a foam drainage Stokes number (Stevenson, 2006) and the last a capillary number. Note that, although Eq. (3) does not represent the only list of four independent groups that can be written using every variable in Eq. (2), it is clear that the unit of foaminess cannot be recovered from any dimensionless groups that can be written and is therefore not an intrinsic property of the foaming solution. Barbian et al. (2003) noted that Σ was strongly dependent upon j_g for mineralised froths (i.e. those with particles attached to gas–liquid interfaces). In fact, in this paper, we will show that we can experimentally obtain almost any value of Σ by manipulating the humidity at the top of the column.

3. The use of foam stability tests to illuminate flotation performance

The link between the stability of a flotation froth and flotation performance has been extensively investigated by the Cilliers group (Barbian et al., 2003, 2005, 2006; Aktas and Cilliers, 2008) who concluded that "flotation performance can be attributed to changes in froth stability". They employed a modified Bikerman test to measure the stability of foam of a mineralised froth, both in the laboratory and on plant. In their method, a column is placed vertically so that its open bottom is located just below the pulp–froth interface, and the height of the foam layer in the column, H, is measured either visually or using an ultra-sonic sensor for online monitoring. Note that there was no humidity control at the top of the column. This device to measure foam stability in a flotation device has been patented by Triffett and Cilliers (2004). It was found that froth height data generally took the form:

$$H(t) = H_{\max}(1 - e^{-t/\tau}) \tag{4}$$

where τ is a time constant for the asymptotic approach to $H_{\max}$. Further, a factor $\beta(H)$ was defined "representing the fraction of air remaining in the froth at a given froth height H", (Barbian et al., 2005, 2006). β relates to the condition at the surface of growing foam, rather than the condition at a specific position within a steady-state froth. They suggested that the velocity of the top of the surface of the froth, u, could be described by the relationship:

$$u = \frac{\partial H}{\partial t} = \beta(H) j_g \tag{5}$$

so that

$$\beta(H) = \frac{H_{\max} - H}{\tau j_g} \tag{6}$$

Barbian et al. (2005) state that "If the froth is highly stable, u (the rise velocity) is equal to the superficial gas velocity in the pulp, j_g." i.e.:

$$u = \frac{\partial H}{\partial t} = j_g \tag{7}$$

suggesting that $\beta = 1$ corresponds to a stable froth. They compared values of β (at a specific height) with values of the fractional air recovery (i.e. the fraction of air that leaves the flotation device within intact bubbles), α. They found a linear (but not equivalent) relationship between α and β; their explanation for the non-equivalence of these parameters (Barbian et al., 2006), that β is measured at only one location on the surface of the frother whereas α is averaged across the entire froth surface, indicates that they would have expected, sampling area being equal, equivalence. The method of measuring foam stability suggested by Barbian et al. has been used for investigations of copper flotation plants by Bartolacci et al. (2008) and Zanin et al. (2009).

Given the importance of froth stability to flotation performance, and the great potential of the device of Triffett and Cilliers (2004) to measure froth stability, it is important to further consider this method. Firstly, Eqs. (5)–(7) are only valid in the limit of zero liquid fraction within the froth when the absolute velocity of the gas is the same as the gas superficial velocity. Secondly, we are of the belief that no equivalence of α and β should be expected or implied. The reason is that we believe the coalescence of bubbles on the surface of a froth to be a highly complex and probabilistic phenomenon that is governed by many factors including the history of the bubbles at the foam surface. The history of a bubble at the surface of a growing foam is dissimilar to that of a foam at the top of a steady-state overflowing foam, and therefore its stability is likely to be different as well. Despite these observations, we believe that Cilliers' method is of great value, and we will show that another factor that foam stability depends on, both in his device to measure the quantity and in other foaming systems, depends on the humidity (or humidity gradient) of the air above the surface of the froth.

4. Experimental method

The apparatus used in the experiments consisted of a chamber of square section with 0.2 m Perspex sides and 0.25 m tall. Above this, the chamber reduced to another column of square section with 0.05 m sides and a height of 0.8 m, as shown schematically in Fig. 1. The column is designed so that the capacity of the chamber (10l) plus the shrinking section (1.8l) is much larger than that of the foam column, so that during every single run, the surfactant and liquid carried up by the foam is negligible compared to the total amount contained in the chamber, thus the surfactant concentration and the liquid level in the chamber can be considered as constant. The location of the foam–bubbly liquid interface was 70 cm below the very top of the column for the initial experiments (although the height of the column was increased for some experiments). Experiments were carried out in a room where the temperature was kept constant at 22.5 ± 1.0 °C. Temperature and relative humidity were measured by a precision humidity/temperature meter (HT-3009, Lutron Electronic). Air was sparged to the base of the column via a humidifier/buffer and a gas frit. A scale was fitted to the side of the column so that the evolution of foam height could be visually recorded. The humidity at the top of the freeboard was adjusted by introducing a stream of dry air via a valve through a specially constructed distribution rose located 0.15 below the top of the column; the dry air was obtained by passing air through a laboratory air drying unit (W. A. Hammond Drierite, US). The flow rates of both the dry air and the humidified air can be manipulated and monitored by adjusting the speed of the air compressors (Model 7524-55, Cole-Parmer Instrument Company, USA). As can be seen in the photograph in Fig. 2, the humidity sensor and small vent passed through a plastic bung at the top of the column. Twelve litres of SDS (Sigma-Aldrich, Germany; 90% purity) solution was used in each experiment.

Bubble size was estimated by taking photos at the bottom of the foam layer and then the photo was zoomed and the bubble size was measured on a computer screen using the software Paint.Net V3.36 (Microsoft Corporation).

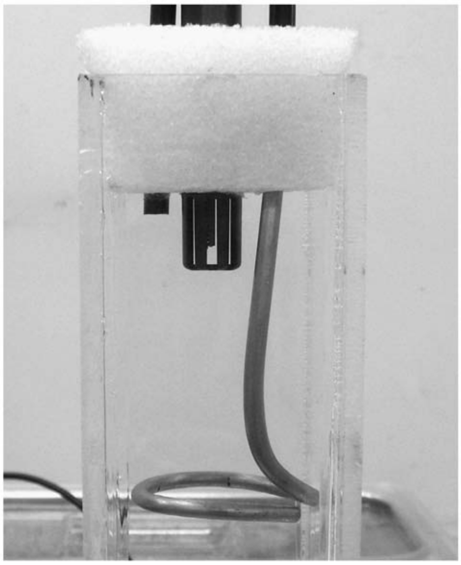

Fig. 2. A photograph showing (from left to right) the vent, sensor of the humidity meter and dry air supply passing through a plastic bung at the top of the column.

5. Results

The evolution of the height of layers of froth stabilised by 2.92 g/l SDS (i.e. 25% above the critical micelle concentration) as a function of j_g in a column in which the relative humidity at the top was fixed at 40% (i.e. 6.8 g of water per kg of bone dry air) is shown in Fig. 3; the column height (i.e. the distance between bubbly liquid–froth interface and the very top of the column) was 70 cm. Arithmetic mean bubble radius varied between 0.35 and 0.45 mm. It is seen that the height grows approximately linearly at first before reaching an equilibrium value, as was observed by many workers including Bikerman (1938).

The relative humidity at the top of the column was raised to 96% (i.e. 17.3 g/kg) to observe what effect the approximate cessation of evaporation had upon foam stability. It was seen (Fig. 4) that, in fact, the foam continued growing in a linear fashion right to the top of the column and that no foam collapse was observed.

Further, the concentration of SDS was decreased to one-tenth of its value for the above experiments (i.e. to 0.29 g/l, corresponding to one-eighth of the critical micelle concentration) and an experiment run at $j_g = 0.053$ mm/s for both relative humidity of 40% and 96%. It was found that, even with such a low surfactant concentration, the foam height increases in a linear fashion with the relative humidity held at 96%, but when the humidity was dropped to 40% it was seen that the foam height approached an equilibrium value (Fig. 5).

These results were investigated further by repeating experiments at $j_g = 0.053$ mm/s and setting the humidity at the top of the column to 40% and using 2.92 g/l SDS, but increasing the height of the column

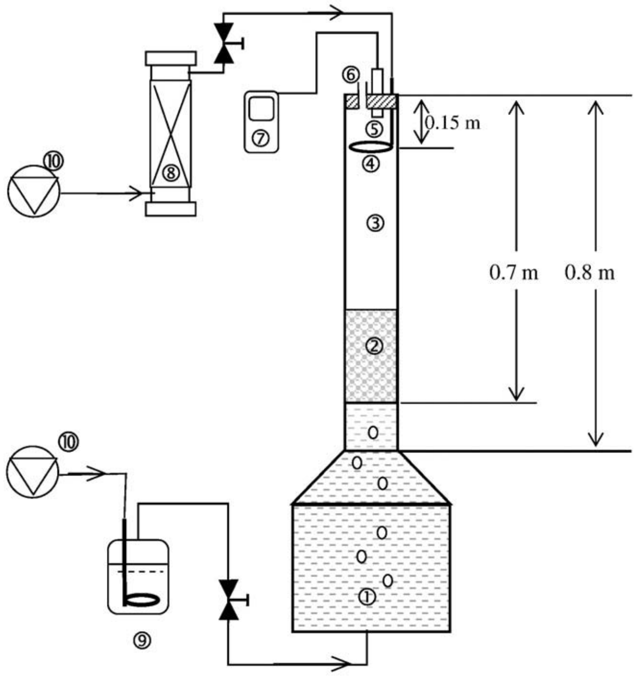

Fig. 1. Schematic diagram of the experimental apparatus. 1. Bubbly liquid; 2. Foam layer; 3. Freeboard; 4. Dry air distributor; 5. Humidity/temperature sensor; 6. Exhaust vent; 7. Humidity/temperature meter; 8. Gas drying unit; 9. Air humidifier/buffer; 10. Air compressors.

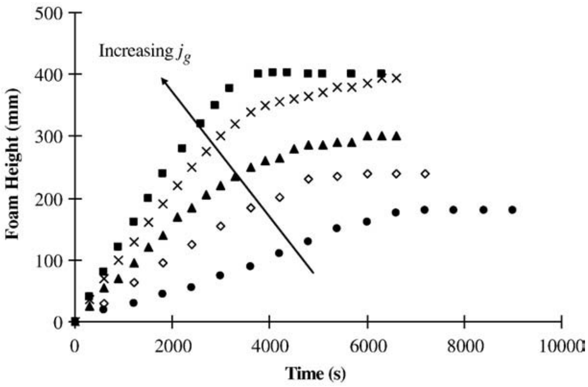

Fig. 3. Foam growth at air superficial velocities of 0.027, 0.053, 0.080, 0.107 and 0.133 mm/s. The column height was 70 cm, relative humidity at the top of the column was 40%, SDS concentration was 2.92 g/l.

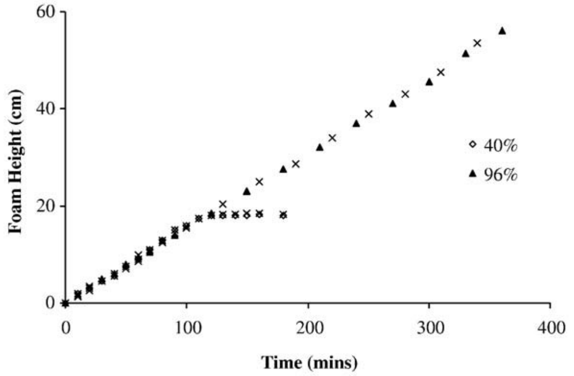

Fig. 4. Growth of a foam stabilised by 2.92 g/l SDS at 40 and 96% relative humidity (shown in the legend), $j_g = 0.027$ mm/s. Cross symbols represent repeats of experiments.

to 0.9 m and 1.2 m. It is seen in Fig. 6 that the equilibrium height can be made to increase by extending the tube (i.e. increasing the height of the freeboard above the foam); when the column height was increased to 1.2 m, foam was still growing after the experiment was stopped after 8.5 h. This result suggests that it is not the absolute value of relative humidity at the top of the column that governs foam stability, but how the relative humidity changes in the freeboard of the column. Subsequently one experiment was conducted to see the axial profile of the relative humidity in the space above the surface of a non-overflow pneumatic froth by varying the position of the sensor of the humidity meter and the result is given in Fig. 7.

6. Discussion

6.1. Experimental results

By inspection of Fig. 3 and Table 1, it is apparent that, for a foam stabilised by 2.92 g/l SDS, the Bikerman unit of foaminess, Σ, does not take a constant value as the gas superficial velocity is varied from 0.027 to 0.133 mm/s. This is consistent with the observations of Barbian et al. (2003) and the implications of the dimensional analysis presented above. It is seen that the unit of foaminess decreases monotonically with increasing gas rate.

The most important finding of these results is that foam stability can be controlled by regulating the relative humidity of the air at the top of the column. By inspection of Fig. 4 it is seen that when the air in the column is nearly saturated (i.e. a relative humidity of 96%), the foam continues to grow in a linear fashion and shows no propensity to collapse. This indicates that the physical process that promotes foam collapse is the evaporation of liquid from the surface of the foam. Thus, the humidity of the air in the freeboard of the column governs the foam stability. Moreover, when the concentration of the surfactant is reduced to 0.29 g/l (Fig. 5), i.e. below the CMC, it is seen that a stable growing foam can be attained when the relative humidity at the top of the column is 96%, whereas the foam attains an equilibrium height when evaporation is encouraged by setting the relative humidity to 40%. Thus evaporation is seen to be a significant factor in governing the stability of a growing foam. In fact, in some of our experiments that lasted for a long time, such as when the column height was increased to 1.2 m and the experiment ran for 8.5 h, small amounts of SDS precipitate were observed at the surface of the foam, which is a direct evidence of evaporation.

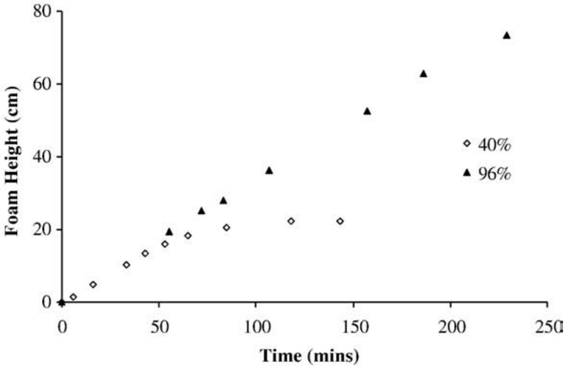

Fig. 5. The growth of a foam made from a lower SDS concentration (0.292 g/l) $j_g = 0.053$ mm/s. The legend indicates relative humidity.

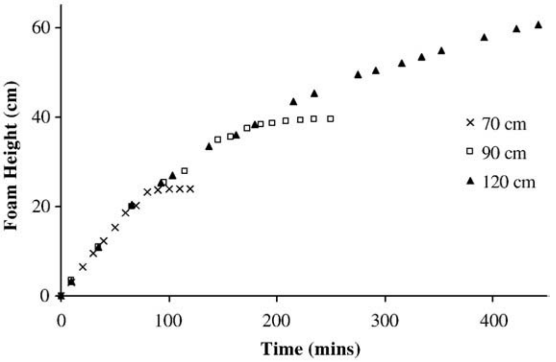

Fig. 6. Foam growth at different values of total column height (i.e. the distance between bubbly liquid–foam interface and the top of the column; shown in the legend). Relative humidity 40%, 2.92 g/l SDS, $j_g = 0.053$ mm/s.

However, by changing the height of the column it is seen that it is not the absolute value of humidity at the top of the column that governs stability. Because foam stability increases when the height of the freeboard increases, it is seen that it is the gradient of humidity that governs foam stability; there is a spatial gradient of relative humidity within the freeboard (Fig. 7). The corollary is that mass transfer of water away from the surface is controlled by diffusion through the freeboard of the column rather than evaporation at the froth surface.

6.2. Implications for froth flotation

Because foam stability in a growing pneumatic foam has been shown to be dependent upon the gradient of humidity in the freeboard of the column, it is clear that Bikerman's 'unit of foaminess' and results from the device of Triffett and Cilliers (2004) share this dependency. Thus it is recommended that these tests are only carried

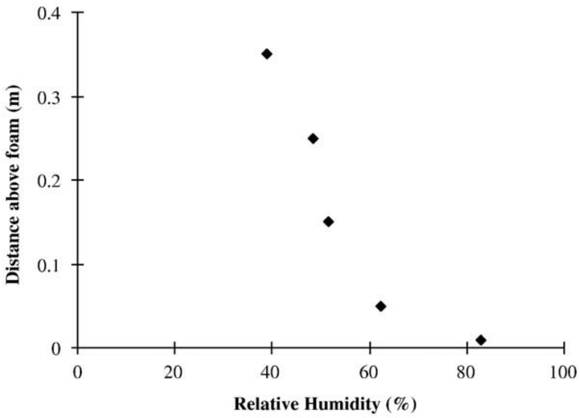

Fig. 7. Relative humidity at different heights in the space above a non-overflowing pneumatic foam stabilised by 2.92 g/l SDS. The column height was 0.7 m, the equilibrium foam height was 0.19 m. $j_g = 0.027$ mm/s. The relative humidity at the top of the column was set to 40%.

Table 1
Bikerman's 'unit of foaminess', Σ, as a function of gas rate for foams stabilise by 2.92 g/l SDS with the relative humidity at the top of the column set to 40%.

j_g (mm/s)	0.027	0.053	0.08	0.107	0.133
Σ (s)	6750	4481	3750	3703	3000

out under conditions of controlled humidity at the top of the column. However, since there has been a demonstrated link between foam stability as measured using the device of Triffett and Cilliers and flotation performance, one may draw the conclusion that relative humidity above the froth can significantly influence how flotation cells operate. It is reasonable to expect that the surface of the foam will be more stable during very humid weather, whereas during dryer metrological conditions one would expect significantly higher rates of surface bubble bursting.

To put the values of relative humidity used in the experiments reported herein into context, monthly maximum and minimum relative humidity values recorded by the Australian Bureau of Metrology (2009) for Mount Isa (the location of major lead, silver, copper and zinc mining operations in outback Queensland) and Cessnock (once a centre of coal mining in the lower Hunter Valley, New South Wales) are given over a twelve month period in Fig. 8. Humidity readings are taken at 9 am and 3 pm each day. It is seen that, at Mount Isa, the maximum relative humidity recorded approaches saturation values during the months of the southern summer (thereby creating conditions for minimal evaporation and maximum froth stability) whereas in the winter significantly lower values of relative humidity are recorded. Relative humidity values recorded at Cessnock display a more uniform humidity throughout the year.

We acknowledge that we have conducted experiments on gas–liquid foams whereas those in flotation devices are mineralised (i.e. they have a surface coverage of particles). However, since equilibrium foam heights are observed in foam stability tests with mineralised froths (Barbian et al., 2003, 2005, 2006; Aktas and Cilliers, 2008) it is suggested that the same mechanism (i.e. evaporation from the surface of the foam) is a governing factor in the stability of mineralised froth.

To proceed further with the analysis of how humidity influences flotation, one needs to be able to predict the rate of bubble bursting on the surface, and this is extremely problematical. Neethling et al. (2005), Grassia et al. (2006) and Neethling and Cilliers (2008a,b), from the same research team, have presented unverified theories for bubble bursting on the free surface of froth. Crucially, none of these studies considers that evaporation from the foam surface can influence foam stability at the surface. Instead, we are guided by the opinion of Cilliers (2009), the pioneer of using physical understanding of froth to describe flotation, who stated that "Developing and verifying models for determining from first principles the rates of surface lamellae failure and internal bubble coalescence remains one of the most challenging aspects of understanding in detail the froth behaviour." We agree with Cilliers, and future work of ours will be directed at addressing this very issue. However, an attempt to model the rate of bubble coalescence in pneumatic froth will not be attempted herein.

6.3. Implications for other methods of foam stability measurement

Bikerman's test is not the only standard method for attempting to quantify the stability of a foam layer. Two methods that are used in quality control in the brewing of beer (Aistrope, 2008) are the Rudin test that was formerly used at the Castlemaine brewery, Queensland, and the NIDEM test that is currently used at the Toohey's brewery in New South Wales, Australia. Weaire and Hutzler (1999) give details of both tests. Both tests are methods to quantify the rate at which the froth later collapses and do so by tracking the rate at which the liquid foam interface rises. This rise is due to the combined effects of liquid drainage and bubble coalescence. However, bubble coalescence at the top of the foam is anticipated to be a dependent upon humidity and therefore a function of humidity. Importantly, such an implication suggests that neither method can provide an intrinsic measurement of foam stability.

Further, the Ross and Miles (1941) test of foam stability involves the pouring of solution onto a liquid surface and measuring the height of foam produced. Provision is made for wetting the walls of the column in order to reduce evaporation. Thus, it is clear that Ross and Miles anticipated a possible dependency of their test upon humidity, but the top of the column is still open to the atmosphere. Rosen and Solash (1969) performed a study of the factors which affected the results of the Ross and Miles test, but air humidity was not considered.

6.4. Implications for the service of gasified beverages

Returning to the observation that, when one pours a carbonated beverage into a vessel, one often observes the threat of foam overspilling only to find that the froth stops growing just at the rim of the glass. The work communicated above suggests a possible explanation for this phenomenon. When the liquid is first poured into the glass, the humidity gradient is low because the height between the top of the foam and the rim of the glass (in effect the freeboard height) is high. However, as liquid continues to be poured into the glass, and froth grows because of bubble nucleation, the freeboard height rapidly diminishes, causing an increase in humidity gradient

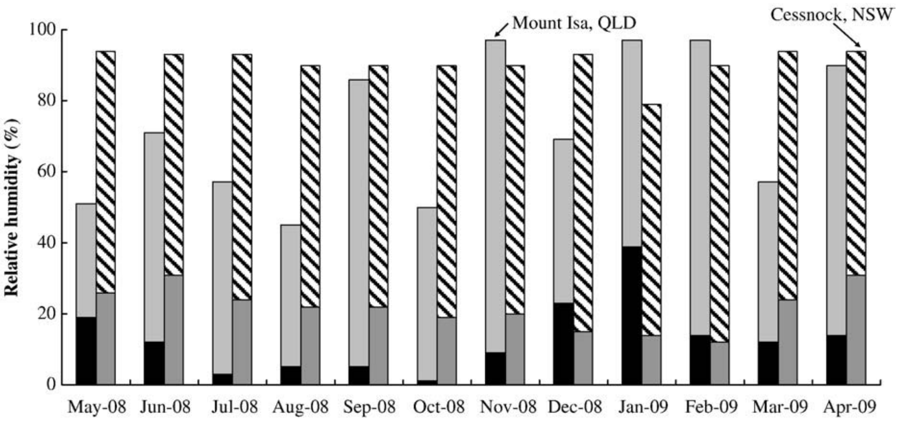

Fig. 8. Monthly maximum and minimum values of relative humidity recorded at Mount Isa, QLD, and Cessnock, NSW, over the period of one year. The left hand bar represents Mount Issa and the right represents Cessnock. The maximum recorded value for that month is the total height of the bar, whereas the minimum recorded value is the height of the sub-bar.

and therefore more evaporation. When the froth just reaches the top of the glass, the evaporation rate is at a maximum, and we suggest that this is the cause of the observation described above. The bitter irony is that, on a very humid day when a refreshing beverage is most sought after, one is more likely to lose volume due to froth overspill than on a less humid day. However, if the beverage is successfully poured, it will retain its head for longer due to lower liquid evaporation from the surface.

An alternative explanation for the foam often only reaching the glass rim is that as the foam expands the films at the surface stretch and the foam gets dryer thereby encourage film rupture. In fact, the reality may be a complex amalgamation of the two physical effects.

7. Conclusions

1. By dimensional analysis, it has been shown that the Bikerman 'unit of foaminess' cannot provide an intrinsic measurement of foam stability.
2. The foam stability value obtained by employing Bikerman's foam test can be manipulated by controlling the value of relative humidity at the top of the column freeboard. One can enhance foam stability by increasing the humidity, indicating that foam collapse is dependent upon the rate of evaporation from the surface.
3. However, by changing the height of the column, it is apparent that it is the humidity gradient within the freeboard that governs the stability, rather than the absolute value of humidity at the top of the column.
4. The observation that foam stability is dependent upon air humidity has important implications for the operation of froth flotation devices and instruments that measure froth stability therein. However, note that, in the device of Triffett and Cilliers (2004), foam stability is dependent upon humidity gradient within the freeboard i.e. the results gained from the device are not only dependent upon the environmental humidity but also the height of the column used.
5. The observation that froth stability is dependent upon humidity has implications for the reproducibility of results from other standard methods to quantify foam stability.

8. Nomenclature

Roman		
g	Acceleration due to gravity	$[\mathrm{m\,s^{-2}}]$
H	Height of a foam layer	[m]
$H_{\max}$	Maximum equilibrium foam later height	[m]
j_g	Gas superficial velocity	$[\mathrm{m\,s^{-1}}]$
r_b	Representative mean bubble radius	[m]
u	Velocity of the surface of a growing foam	$[\mathrm{m\,s^{-1}}]$
t	Bubbling time	[s]
Greek		
α	Fraction of air that overflows in intact bubbles	[]
β	The fraction of air remaining in the froth at a given froth height	[]
ρ	Liquid density	$[\mathrm{kg\,m^{-3}}]$
μ	Liquid dynamic viscosity	[Pa s]
Σ	Bikerman's 'unit of foaminess'	[s]
τ	Time constant of asymptotic approach to $H_{\max}$	[s]

Acknowledgments

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References

Aistrope, M., 2008. Personal communication, 28th–29th August.

Aktas, Z., Cilliers, J.J., Banford, AW, 2008. Dynamic froth stability: particle size, airflow rate and conditioning time effects. Int. J. Min. Proc. 87, 65–71.

Australian Bureau of Metrology 2009 www.bom.gov.au/climate/dwo/index.shtml, Accessed 11th May 2009.

Barbian, N., Ventura-Medina, E., Cilliers, J.J., 2003. Dynamic froth stability in froth flotation. Min. Eng. 16, 1111–1116.

Barbian, N., Hadler, K., Ventura-Medina, E., Cilliers, J.J., 2005. The froth stability column: linking froth stability and flotation performance. Min. Eng. 18, 317–324.

Barbian, N., Hadler, K., Cilliers, J.J., 2006. The froth stability column: measuring froth stability at an industrial scale. Min. Eng. 19, 713–718.

Bartolacci, G., Ourriban, M., Knuutila, D., Lockhart, A., Finch, J.A., Lau, C.H., Fortin, A., Goyette, G., 2008. The link between pulp zone hydrodynamic characteristics and froth stability in a 125 m^3 flotation column. Proc. 40th Annual Meeting of Canadian Mineral Processors, January 23–25, Ottowa, Ontaria, Canada.

Bikerman, J.J., 1938. The unit of foaminess. Trans. Faraday Soc. 34, 634–638.

Bikerman, J.J., 1973. Foams. Springer-Verlag.

Blanco-Gomis, D., Mangas-Alonso, J.J., Junco-Corujedo, S., Gutierrez-Alvarez, M.D., 2009. Characterisation of sparkling cider by the yeast type used in taking foam on the basis of polypeptide content and foam characteristics. Food Chem. 115, 375–379.

Buckingham, E., 1914. On physically similar systems; illustrations of the use of dimensional equations. Phys. Rev. 4, 345–376.

Cilliers, J.J., 2009. Physics-based froth modelling: new developments and applications. Int. J. Comp. Fluid Dynamics 23, 147–153.

Exowera, D., Kruglyakov, P.M., 1997. Foam and Foam Films. Elsevier.

Grassia, P., Neethling, S.J., Cervantes, C., Lee, H.T., 2006. The growth, drainage and bursting of foams. Colloids Surf. A 274, 110–124.

Hansen, B.B., Kiil, S., Johnsson, J.E., Sonder, K.B., 2008. Foaming in wet flue gas desulfurization plants: the influence of particles, electrolytes, and buffers. Ind. Eng. Chem. Res. 47, 323903246.

Morales, R.D., Rodriguez-Hernandez, H., Vargas-Zamora, A., Conejo, A.N., 2002. Concept of dynamic foaming index and its application to control of slag foaming in electric arc furnace steelmaking. Ironmak. Steelmak. 29, 445–453.

Neethling, S.J., Cilliers, J.J., 2003. Modelling flotation froths. Int. J. Min. Proc. 72, 267–287.

Neethling, S.J., Cilliers, J.J., 2008a. Predicting air recovery in flotation cells. Min. Eng. 21, 937–943.

Neethling, S.J., Cilliers, J.J., 2008b. Predicting air recovery in flotation cells. Min. Eng. 21, 937–945.

Neethling, S.J., Lee, H.T., Grassia, P., 2005. The growth, drainage and breakdown of foams. Colloids Surf. A 263, 184–196.

Rosen, M.J., Solash, J., 1969. Factors affecting initial foam height in the Ross–Miles foam test. J. Am. Oil Chem. Soc. 46, 399–402.

Ross, J., Miles, G.D., 1941. An apparatus for comparison of foaming properties of soaps and detergents. Oil & Soap 18, 99–102.

Stevenson, P., 2006. Dimensional analysis of foam drainage. Chem. Eng. Sci. 61, 4503–4510.

Stevenson, P., Galvin, K.P., 2007. On empiricism in minerals processing research. Min. Eng. 20, 776–781.

Tamura, T., Kaneko, Y., Nikaido, M., 1997. Stability factors of foam film in contrast to fluctuation induced by humidity reduction. J. Colloid Interface Sci. 190, 61–70.

Triffett, B.B., Cilliers, J.J., 2004. Measuring Froth Stability, International Patent Application Number: PCT/ AU2004/000331.

Weaire, D.L., Hutzler, S., 1999. The Physics of Foams. O.U.P.

Zanin, M., Wightman, E., Grano, S.R., Franzidis, J.R., 2009. Quantifying contributions to froth stability in porphyry copper plants. Int. J. Min. Proc. 91, 19–27.