WET GUM LABELLING OF WINE BOTTLES

It is shown that bubbling on wine bottle labels is due to absorption of water from the glue, with subsequent hygroscopic expansion. Contrary to popular belief, most of the glue's water must be lost to the atmosphere rather than to the paper. A simple lubrication model is developed for spreading glue piles in the pressure chamber of the labelling machine. This model predicts a maximum rate for application of labels. Buckling theory shows that the current arrangement of periodic glue strips can indeed accommodate paper expansion. Some recommendations follow on the paper, the glue, the labelling rate and the drying environment.

1. Introduction

The problem of bubbling on labels is endemic to the bottling industry. Immediately after they emerge from the labelling machine, the labels normally appear to be adhering smoothly to the glass bottles, with a good even coverage of glue. However, in a significant number of cases bubbles first appear after ten to fifteen minutes. Although there is much variation, bubbles are typically 5 mm wide, a few mm in height and 15 mm in length. Usually they are at least 20 mm from a label edge, but otherwise have no obvious pattern of distribution. This disfigurement is at odds with the desire of Southcorp Wines Pty Ltd to present a high quality product. Some shipments of wine have been returned by dissatisfied customers simply because of the imperfect labels. Since label bubbling is prominent in around one in twenty labelled batches throughout the whole bottling industry, there are important economic implications. In some instances, batches of label paper and glue have been recalled after their quality has been questioned. Hence, this problem is of interest not only to wine producers but also to printers, paper manufacturers and glue manufacturers. Meetings for this project at the MISG were attended by Herbert Hruby of Southcorp Wines, Wolf Viergever of AQ Printworks and Warren Kidd of NB Love Adhesives.

What is wrong with the 5% of label batches that misbehave? No-one knows for certain. It is widely believed that water uptake and hygroexpansion of the paper is involved. Although bubbles may form 15 minutes after application, it is observed that bubbles may expand or contract over periods of several days in response to changes in atmospheric humidity. Secondly, glue temperature and glue wetness at the time of application are known, by experience, to be important factors. For example, Viergever (1995) recommends that the glue storage temperature should be close to the bottling line temperature, between 18°C and

28°C. Anecdotal evidence suggests that label bubbling tends to be worse with white wines that are bottled at lower temperatures than red wines. The project group surmised that the most relevant temperature-dependent property would be glue viscosity, which might influence the spread of glue strips on the bottle.

In the bottling plant, label quality is controlled largely by trial and error. Adjustable parameters include labelling rate, pressure applied to labels, water content of glue and paper thickness and density. Drying may be assisted by fans. A rational mathematical model is desirable if the relative importance of these parameters is to be understood.

2. Spreading of glue piles

In the labelling of Australian foodstuffs, casein glues are commonly used. Alkaline caseinate solutions are formed from casein protein that occurs naturally in milk. This glue has a number of advantages, including plentiful supply, safety for use in food packaging, solubility in alkaline bottle-washing solutions, and low viscosity for ease of spreading. It is highly regarded for its resistance to water in ice buckets. However we found that dry glue could easily be removed from glass by wetting, suggesting that the varnish layer on the paper is largely responsible for passing the ice bucket test. According to Salzberg (1976) wet casein glues are near-Newtonian, having little variation in viscosity at low concentrations, but they become non-Newtonian at high concentrations. In the Southcorp Nuriootpa bottling plant and at most others, a glue pallet, charged with glue, applies glue to a label in regularly spaced strips, approximately 0.6 mm in width and 1.5 mm apart. The label is then drawn away from the glue pallet by mechanical finger grips, leaving mounds of glue on the paper (Figure 1). The periodic glue lines and the grip marks are visible through the back of a labelled bottle. The label is then placed on the bottle and pressure is applied to its face to spread the glue, which is sandwiched between the glass and the label, and to achieve an intimate wrinkle-free contact between glass, glue and label. Sponges and brushes are used to do this and finally, as an added measure, the bottles are placed in a pressure chamber in which a curved rigid wall is pressed against the label. Bottles emerge from the pressure chamber with wrinkle-free labels but wrinkles often appear later. Our concern is to determine the effectiveness of the applicators for spreading the glue.

As we shall verify in subsequent calculations, the glue mounds are rapidly flattened during the intial stages of compression. Therefore we assume that almost immediately after the glue mounds on the label make contact with the glass bottle, they are flattened into an almost rectangular shape of width $2L_0$ and height h_0, determined by the initial sectional area $A = 2h_0L_0$ of the mound.

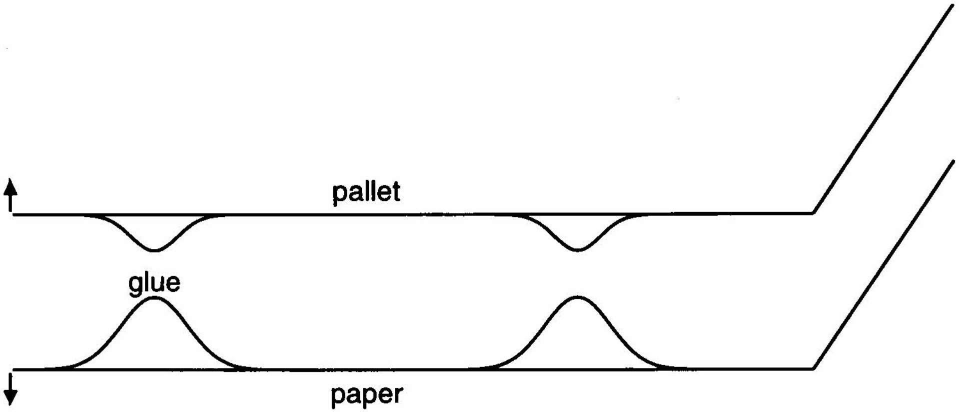

Figure 1: Application of glue.

Subsequently each glue strip is subjected to a force F (assumed fixed) by the pressure devices which causes the glue to spread. We are interested in the effectiveness of these devices during the squeezing stage of the process.

From standard lubrication theory (e.g. Longwell, 1966), the Navier-Stokes equations reduce to

$$\frac{\partial p(x,t)}{\partial x} = \mu \frac{\partial^2 v_1(x,y,t)}{\partial y^2} \tag{1}$$

where p is the pressure, μ is the dynamic viscosity, t is the time, (x, y) are Cartesian coordinates and v_1 is the x-component of fluid velocity.

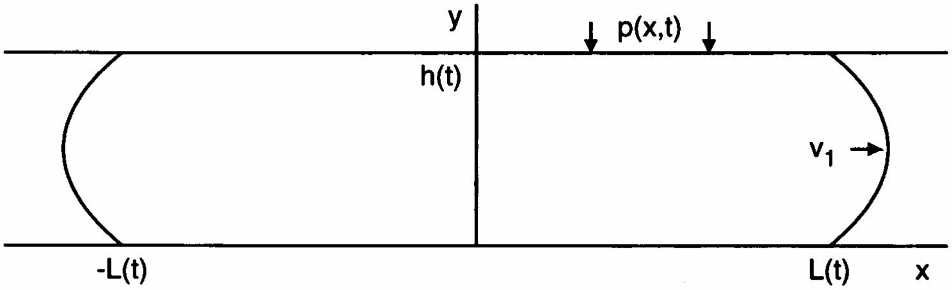

Figure 2: A glue pile in the pressure chamber.

Consider the material flowing into and out of a thin strip of width Δx, depth Z and height $h(t)$. The rate of change of glue volume in the region $(x, x + \Delta x) \times (0, h(t)) \times (0, Z)$ is $Z\Delta x \; dh/dt$, which must equal the rate of material flowing in minus the rate of material flowing out. This gives

$$Z\Delta x\frac{dh}{dt} = Z\int_0^{h(t)} v_1(x,y,t)dy - Z\int_0^{h(t)} v_1(x+\Delta x,y,t)dy.$$

Dividing through by $Z\Delta x$ and taking the limit as $\Delta x \to 0$, we obtain a simple form of the equation of continuity (e.g. Longwell, 1966), a local conservation law

$$\frac{dh}{dt} + \frac{\partial Q}{\partial x} = 0 \tag{2}$$

where

$$Q(x,t) = \int_0^h v_1\ dy. \tag{3}$$

Now by twice integrating throughout (1) and respecting the conditions $v_1 = 0$ at $y = 0, h$ we obtain

$$v_1(x,y,t) = \frac{1}{2\mu}\frac{\partial p}{\partial x}y(y-h(t)). \tag{4}$$

Consequently,

$$Q(x,t) = -\frac{1}{12\mu}\frac{\partial p}{\partial x}h^3(t) \tag{5}$$

and then (2) implies

$$\frac{\partial^2 p}{\partial x^2} = \frac{12\mu}{h^3}\frac{dh}{dt}. \tag{6}$$

Integrating throughout (6) and noting $p = 0$ when $x = \pm L(t)$, we arrive at

$$p = -\frac{6\mu}{h^3}\frac{dh}{dt}(L^2 - x^2). \tag{7}$$

Now the total force applied to a glue strip is

$$\begin{aligned} F &= Z\int_{-L}^{L} p\ dx \\ &= -\frac{8\mu Z}{h^3}\frac{dh}{dt}L^3 \end{aligned}$$

where Z is the length of the label.

Assuming $h(t)L(t) = A/2$, where A is the constant cross-section area of the glue pile, we have the ordinary differential equation

$$\frac{1}{h^6}\frac{dh}{dt} = -\frac{F}{\mu Z A^3} \tag{8}$$

with solution

$$H = (1 + 5T)^{-1/5} \tag{9}$$

where $H = h/h_0$, with h_0 the initial height and $T = t/t_s$, with t_s a natural time scale for glue spreading,

$$t_s = \frac{\mu Z A^3}{F{h_0}^5}. \tag{10}$$

Thus, although the initial spreading rate is very rapid, justifying our earlier assumption of an initially flattened profile, the spread rate becomes very slow after a time of order t_s. Explicitly at time t_s the width of the glue pile increases by a factor $(1+5)^{\frac{1}{5}} \approx 1.4$ (a 40% increase) whereas an additional 40% increase would not be achieved until six times this period t_s. The period t_s (or close to it) thus represents the optimal effective application time for F; there being little point in adopting a smaller application time (thereby underutilizing the device) or in uselessly increasing the processing time for labels. It is also clear that glue spreading by compression, although important, is limited. An adequate glue cover will not be achieved by applying larger glue piles that are more widely separated. The effectiveness of various glue spreading strategies can be examined using (10). The strong dependence of t_s on h_0 is especially significant. For glue strips of a fixed width, lower glue mounds are signicantly more difficult to spread.

Since the optimal processing time for a label is close to t_s, the number of labels that should be processed per unit time under optimal operating conditions is approximately t_s^{-1}. In terms of the mean pressure P applied to the label, the maximum labelling rate in labels per unit time is

$$R_{max} = \frac{{h_0}^5 P X}{N \mu A^3} \tag{11}$$

where X is the label width in the x-direction and N is the number of glue strips on each label. We suggest that this speed is near optimum since (8) predicts that little extra benefit will be gained by longer compression times. We were able to measure all of the quantities appearing in (11) except the pressure P. We recommend that the operating pressure P of the label pressure chamber be measured by a consultant. If we assume that P is of the order of the pressure applied by a human finger (this is the true rule of thumb!), then the speed limit is of the order of 180 per minute. However, since the speed limit is directly proportional to pressure, measurement of the latter is important. Note also that speed limit is inversely proportional to glue viscosity which is strongly temperature dependent. For example, measurements taken at NB Love Adhesives show that the viscosity of the glue GRIPIT 1340 reduces from 2.84×10^3 ps at 10°C to 3.6×10^2 ps at 30°C.

3. Water transport from glue to paper and atmosphere

Since the glue strips are around 0.6 mm wide and the paper is 0.1 mm thick, it is valid to assume a one-dimensional model for horizontal absorption of liquid into the paper. Absorption by capillary action of a porous medium at water content $\theta(y,t)$, defined as the volumetric proportion of the local region occupied by water, is governed by a nonlinear diffusion equation (e.g. Philip, 1969)

$$\frac{\partial \theta}{\partial t} = \frac{\partial}{\partial y}\left[D(\theta)\frac{\partial \theta}{\partial y}\right] \tag{12}$$

subject to $\theta = \theta_0$ (constant saturated value) at $y = 0$ and $\theta = \theta_i$ (initial water content) at $t = 0$.

At early times, the solution must agree with the similarity solution appropriate for the semi-infinite domain. Hence with θ a function of $y\sqrt{t}$ at early times, the total volume of water absorbed per unit cross-section area must take the form

$$i = St^{\frac{1}{2}} + O(t),$$

where S is the experimentally measurable sorptivity (Philip, 1957) that depends only on θ_i and θ_0, and on the shape of $D(\theta)$. We guess that the average capillary properties of paper may be approximated by those of a silty clay loam, for which $S \approx 10^{-4}$ m/s$^{1/2}$ (White and Broadbridge, 1988). At this rate, water would proceed to saturate the thin label in around 1 second. This was borne out by our own experiments in which labels in contact with free water curled in 2 seconds. However, D scales like inverse viscosity μ^{-1}, (Philip, 1969) from which it follows that S scales like $\mu^{-\frac{1}{2}}$ and absorption time scales in proportion to μ. Casein glue, with a viscosity of 10^5 cp, compared to 1 cp for water, would take a day to saturate the paper. What is observed is that hygroscopic deformation of labels first occurs after 15 minutes. This corresponds to absorption of a liquid of intermediate viscosity 10^3 cp. We suggest that the paper is acting as an imperfect filter, allowing a little casein to enter with the water, but leaving behind a more concentrated glue.

After the glue has been applied and the label has been pressed to the bottle, the glue must dry so that it can form a rigid gelatinous bond. It is commonly believed that most of the glue water, lost during the period of gel formation, is taken up by the paper label. Eurokete label paper has a Cobb value of 25 g/m^2 (or 0.25 mm equivalent water depth). The Cobb value is defined to be the level of water uptake in paper in contact with free water for 60 seconds, enough time for saturation to occur. On the evening of Tuesday 30 January 1996, a number of glued labels emerging from the glue pallet in the Nuriootpa plant, were measured to have a glue mass of 2 ± 0.5 g. Since Casein glue is approximately 65% water by volume, this corresponds to a water level of 130 g/m^2, five times the Cobb value of the paper. Only around 20% of the glue water will be absorbed by the paper in the important early stages of glue drying. This may increase viscosity by two orders of magnitude (Salzberg *et al.,* 1974). However, most of the water must eventually be removed by atmospheric drying. Hence it is important to leave channels between the glue strips and to provide a drying environment after packing bottles. Since the upper surface of a label is varnished, drying can only occur at the edges. If the solar radiation constant is converted to latent heat, the equivalent evaporation rate is 0.4 cm/day. Rates of 1 cm/day are observed over desert soils. With extra drying assistance, drying could be expected to proceed to the centre of labels in around 5 days. This agrees with the observed bubble response times as atmospheric conditions change.

4. Deformation of labels

Considerations here are very similar to those of the "Piping in Newsprint Rolls" problem of MISG 1988 (Barton, 1989). By analogy with that problem, it is already clear that enough water is available to cause visible hygroexpansion in the paper labels. There are some significant differences between that problem and the current one. Unlike the newsprint rolls problem, there is glue present and this will help to prevent sliding of the paper sheet. The glue is applied in periodic strips and the question arises whether this is a good design for preventing paper buckling as it absorbs water and expands. Also unlike that in the newsprint problem, the top surface of the paper is varnished.

Because of the varnish, the upper surface is more rigid, so that there is a tendency for the paper to curl away from the bottle. In fact, the expansion is highly anisotropic. Due to the stresses applied in the paper production process, the wood fibres align preferentially in one direction. The paper is more rigid in the fibre direction and expansion occurs predominantly in the transverse direction. With the bottle axis vertical, labels are always printed so that the fibre direction is horizontal. Then when labels are attached to the cylindrical bottle surface, the curvature assists reinforcement against the lift-off curl about a horizontal axis, as the paper expands vertically.

It is recommended by the bottling machine manufacturer that glue strips should be applied transverse to the wood fibres, as this provides reinforcement against hygroexpansion. On the other hand, glue strips parallel to the wood fibre direction could well weaken the cross-fibre hydrogen bonds, thereby enhancing paper deformation. It is found that a number of wine producers currently ignore this advice from the labeller manufacturer, as their glue pallets produce horizontal strips parallel to the fibres.

In our own test, after 60 seconds immersion in water, a label expanded by 0.7% in the direction parallel to one edge, but with no noticeable expansion in the orthogonal direction. This expansion would be enough to accommodate a semi-circular cylinder of diameter 1.2 cm on an initially flat 10 cm × 10 cm label.

When a sheet of paper absorbs water, it expands in the direction transverse to the fibres, with resulting strain $\varepsilon = \Delta L/L$. If the paper is not free to expand indefinitely, it must be experiencing a compressive stress P. An unattached length L of paper will eventually buckle when the load reaches a critical value. Linear elasticity theory has previously been applied to paper buckling at the 1988 MISG (Barton, 1989). For a beam of length L and thickness d, the critical stress for buckling is

$$P_c = \pi^2 EI/L^2 \tag{13}$$

where E is Young's modulus (approximately 2×10^9 N/m^2 for paper) and $I = d^3/12$. In linear elasticity theory

$$P = \varepsilon Ed. \tag{14}$$

Hence for a strain ε, the critical length of unattached sheet at the onset of buckling is

$$L_c = \frac{\pi d}{2\sqrt{3\varepsilon}}, \tag{15}$$

independent of Young's modulus. If the glue strips remain attached, and expansion takes place transverse to the strips, then buckling will first occur when ε is large enough so that L_c is the length of unattached sheet (approximately 1.5 mm) between the glue strips. For paper of thickness $d = 100$ μm, this occurs when the strain is 3.7×10^{-3}, around half the expansion that we observed in fully wetted labels.

For simplicity, we take the shape of a buckle to be a circular segment as shown in Figure 3(a). For a circular segment of small angle,

$$h^2 \approx 3\varepsilon L^2/8. \tag{16}$$

For fully wetted paper with $\varepsilon \approx 7 \times 10^{-3}$ and with glue strips attached, the buckle height will be approximately 80 μm, slightly less than the paper thickness (typically 80–100 μm). Hence, with an unattached sheet of this length between glue strips, swelling may be accommodated without noticeable visual effects. When the critical buckling length decreases to less than $2L$ (Figure 3(b)), a detached central glue strip may be lifted. By combining (15) and (16), at the onset of buckling, the paper will lift a distance

$$h = \frac{\pi d}{4\sqrt{2}} \tag{17}$$

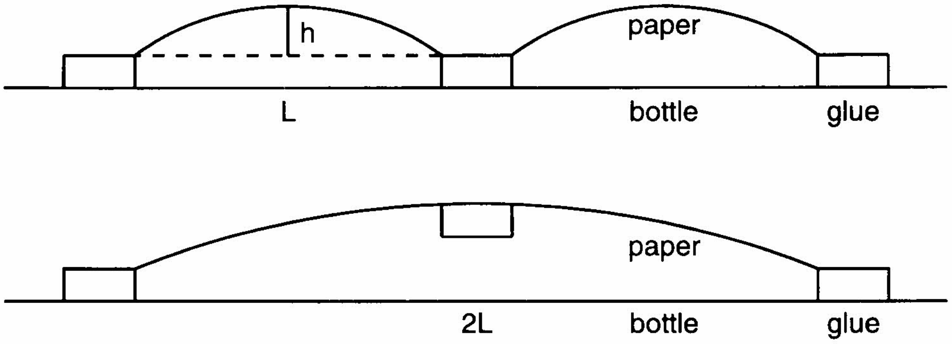

Figure 3: Buckling of the sheet between glue strips. (a) Secure strips. (b) Central strip detached.

which depends only on the paper thickness. From (16), when the strain increases to the value 7×10^{-3} for fully wetted paper, h will increase to 160 μm. We suggest that this is the mechanism by which glue strips are first threatened. However, a full analysis would require more information on the strength of the glue-bottle bond at various water contents. If the glue strips are transverse to the paper fibres, then this mechanism is inapplicable, as expansion across the glue strips will be negligible. In this case, a model would use the theory of buckling under a horizontal stress (caused in this case by the paper expansion, and maintained by adhesion) against a vertical load (maintained by the glue restoring force). Furthermore, the glue is expected to be visco-elastic, and the glue strips may be under longitudinal tension after drying. We recommend experimenting with glue strips that have several thin cuts to reduce longitudinal tension.

5. Conclusions and recommendations

The deformations observed in labels are entirely consistent with water absorption and subsequent hygroscopic expansion of the label paper transverse to the direction of the paper grains. There is more than enough water in the glue layer to fully saturate the paper labels. Most of the excess water must eventually be removed by atmospheric drying. Therefore, we recommend that labelled bottles continue to be stored in a good drying environment, with good ventilation. Since the paper deformation is due to water absorption, we recommend experimenting with labels that have impermeable coatings on both faces. At present, only the printed side is coated with varnish. If the underside is impermeable, the paper will not assist the glue drying, so that glues with lower water content may be needed.

It is already established that glue temperature is an important determinant of glue quality. This strongly suggests that glue viscosity is important, so that glue spreading must be a key step in glue application. Our simple model predicts a near-optimum labelling rate given in (11). With the exception of pressure applied to the label, most of the parameters appearing in this equation are known. We recommend that the applied pressure in the final pressure chamber be measured, so that the labelling speed limit can be calculated.

There are several reasons why the glue should continue to be applied in strips. The spaces between strips promote drying, and they allow compressed air to escape, thereby avoiding "wallpapering bubbles". The strip arrangement can accommodate hygroscopic paper expansion without visible deformation. However, the strips should be applied transverse to the paper fibre direction, in order to reinforce the paper against expansion. Hence, we recommend that the strips should be applied in the direction of the bottle axis. We suggest that the continuity of glue strips in the longitudinal direction should be broken by cuts, in order to reduce the effects of longitudinal glue tension.

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