IMPROVING THE DESIGN AND OPERATION OF A TWEEDY DOUGH MIXER

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Compared with other cereals, wheat is special because the dough that it makes, when mixed with water and other ingredients, has the following unique properties:

1. It forms a viscoelastic material.
2. It has good gas retention since the diffusion of gases through the dough is small.
3. It sets when cooked to form a solid foam.

In the study of dough rheology, mixing and baking, each of these properties generates the need for different types of mathematical considerations. For the Goodman Fielder problem presented at the 1997 Mathematics-In-Industry Study Group (MISG) meeting at Melbourne University, it is the first of these three properties which plays the crucial role in any study of the efficiency of the mixing of wheat flour dough.

The group studied the mechanics associated with the mixing of a large 300 kg dough mass within a Tweedy mixer rotating at 360 rpm subject to a cycle time of 4 minutes and concluded:

1. The baffles along the side of the mixing chamber are essential for the elongation strains necessary for dough development.
2. The impeller blades should have a circular rather than rectangular cross section to reduce the stress concentrations in the viscoelastic dough mass that lead to a cutting rather than stretching motion.
3. A series of experimental tests needs to be performed to study the effects of: baffle geometry; mixing speed; and recirculating motions within the mixing chamber.

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1. Introduction

Modern bakery environments produce more than 8,000 bread loaves per hour every day throughout the country. The ambient conditions and ingredients vary significantly and this impacts on both the final product quality and profitability. A crucial step in the manufacture of bread is the *development* of the proper dough texture prior to baking in order for the CO_2 and other gases to produce an acceptable bubble structure and firmness.

The primary solid ingredient in bread is wheat flour, which is a mixture of proteins such as gluten, carbohydrates in the form of starch, and lipids such as butter and oil. The percentage of protein and carbohydrate varies with the type of wheat and the growing conditions, but for Australian bread-making wheats this distribution is typically 11% protein with the balance being 74% carbohydrate and 15% bran.

1.1 Mixing and dough development

The bread making process commences with the mixing of a dough. Water, oil, salt, yeast, and other additives such as ascorbic acid are added to the flour in a mixer (Moss *et al.*, 1981). After an initial hydration stage, the ingredients combine to form a dough mass which exhibits elements of both solid and fluid behavior. The technical term for such a material is a thixotropic fluid, and models of these are widely used in the study of the rheological flows that occur during the processing of viscous polymer solutions. The dough mass is mixed at high speed until the gluten forms a cross-linked network surrounding the starch and the other proteins and lipids in the flour. The presence of the salt, the water, and to a lesser extent, the other other additives is crucial to formation of the crosslinked gluten network.

Dough development, which is the term used to describe the processes by which the dough reaches proper gluten microstructure, involves a combination of mechanical, chemical, and biological changes to the flour constituents comprising the dough mass (Institute, Bread Research, 1991; Williams, 1975). A properly developed dough is a cohesive elastic network that can be stretched into a very thin film. A micrograph of a thin dough film in Figure 1 shows that the dark stained gluten molecules are aligned in a predominant direction and form a highly cross-linked network with the lighter colored starch and lipid molecules occupying the space between networked chains. If the dough is mixed for an excessively long period of time *overdevelopment* occurs and the dough is no longer strong enough to retain the gas bubbles generated during baking. On the other hand, insufficient mixing fails to produce a sufficiently cross-linked network, and the dough is *underdeveloped.*

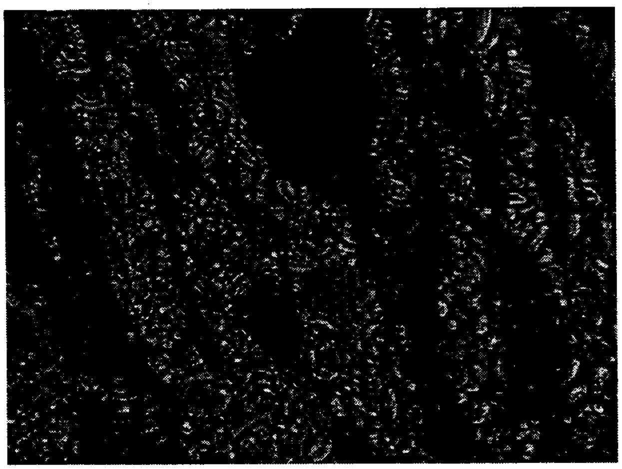

Figure 1: Micrograph of a dough at peak development.

Dough development has traditionally been accomplished by three primary means depending upon the type of flour and the predominant baking culture. All development processes involve some combination of mechanical work and chemical reactions in order to stretch the gluten chains into an extended and cross-linked three dimensional network. The major development methods may be broadly grouped into the following categories:

- **Chemical fermentation**: Doughs made from "strong" wheats with high protein contents are traditionally allowed to ferment for several hours before being worked slightly and then divided for baking. This is the traditional bread making technique, and in North America it remains the primary method of production.

- **Moderate speed mixing**: Doughs made from moderately hard wheats, which includes most Australian wheats, are hydrated in a mechanical mixer after which the dough is then mechanically kneaded for 8–15 minutes depending upon the mixing device. The dough is then processed immediately without additional fermentation or rest periods prior to baking.

- **High speed mixing**: The Chorleywood process, developed in England for softer wheats, uses an under four-minute high-speed, 360 rpm, mixing cycle to produce a developed dough mass, which can be divided, and proofed into baking tins within ten minutes of the mixing cycle.

The problem presented by Goodman Fielder to the MISG focused primarily on the mechanical processes involved in dough making. The important biological and chemical processes were not examined.

1.2 The Chorleywood process

The Goodman Fielder company uses the Chorleywood process in all their major metropolitan facilities. The decision to adopt this process was made on economic grounds since it allowed existing production levels and product quality to be maintained with a minimum of equipment and capital expenditure.

The Chorleywood process mixes approximately 360 kg of dough in less than 4 minutes in a large Tweedy mixer, which was originally designed for the mixing of polymeric resins, but has been adapted for bread making. Figure 2 shows a picture of the interior of a one-tenth scale research mixer. The production line mixers consist of a variety of specific models of various ages, but they are all capable of delivering a 300 kg dough mass within 4 minutes. The mixer comprises an upright, cylindrical, jacketed chamber in which is located a bottom driven horizontal turning plate and vertical spiral impeller fixture rotating at 360 rpm. The base plate is shown schematically in Figure 3. Three angled baffles are fixed to the side walls and act to deflect the dough back into the center of the mixer.

Figure 2: Interior of a Tweedy mixer.

The ingredients, including flour and refrigerated water are automatically charged into the fully sealed mixer. After approximately two minutes of mixing, a partial vacuum of between 0.3–0.5 atmospheres is drawn to remove large air packets entrained in the dough mass and to produce the fine air bubble structure necessary for the production of a good bread loaf.

The mixers operate to a fixed power usage criterion. For the Tweedy mixer, it is an empirically observed fact that a minimum of 43 kJ or 12 wt-hours of mechanical work by the mixer must be imparted to each kilogram of dough in order to obtain a satisfactorily developed bread dough. During the mixing cycle, the rate of energy input increases dramatically for the first 30 seconds while the ingredients are hydrated and then stabilises for the remaining mix time.

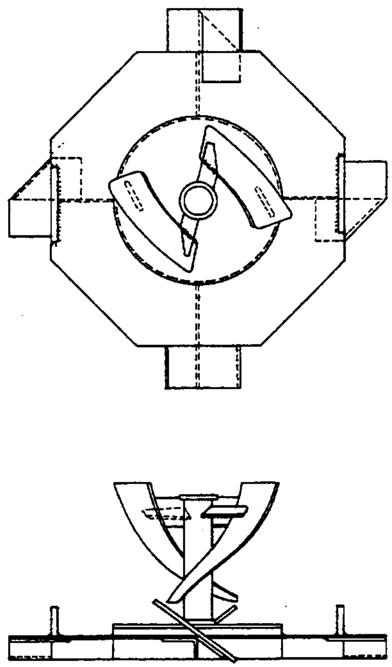

Figure 3: Schematic drawing of the base plate.

The ideal finish temperature of the dough at the completion of mixing is 31°C. At this temperature fermentation processes remain under control and do not become excessive during the subsequent processing prior to baking. In order to meet this important constraint, many of the liquid ingredients are kept refrigerated until introduction into the mixer. During warm weather, even the use of ice water is insufficient to prevent overheating and consequently a number of bakeries deliberately underdevelop their doughs. However, this produces an inferior dough.

Additional problems are occasionally encountered during the mixing of the dough mass when the power consumption of the mixer can drop substantially for a period and thus lengthen the amount of time necessary for the energy usage criterion to be met. It is believed this behavior is associated with the rigid rotation of the dough mass on top of the impeller rather than between the impeller and baffles.

1.3 The problem definition

Goodman Fielder posed two questions in relation to the use of Tweedy mixers and the requirement of a four-minute mixing cycle.

1. Are there mixer configuration changes such as structural baffle configuration, impeller design, and rotational speed settings that could be altered to improve efficiency and overall product quality?
2. What can be done to improve the quality of the work input from the Tweedy mixer to the dough, and thereby alleviate the excess rise in temperatures experienced in some bakeries?

2. The mixing process

Since the industrial mixing process is normally accomplished in a sealed and partially evacuated chamber, direct visualization of the mixing in a full scale machine is not possible. However, the Goodman Fielder research laboratory have a 1/10th scale mixer, which was used to obtain video data of a mixing cycle. Greg Pointing, the Goodman Fielder representative, also provided video data of several other types of moderate speed mixers belonging to their research laboratory.

The interior of the research mixer is shown in Figure 2. A drawing of the base plate and impeller, which occupy approximately the bottom 2/3 of the chamber, are shown in Figure 3. Several baffles, three in the case of the research mixer, protrude from the walls into the mixing cavity a distance of 15–20% of the chamber radius. The geometric ratios of the impeller dimensions and the baffle configurations of the research mixer are comparable to those of the full-sized mixer. Since the dimensions of both mixers are much larger than the characteristic lengths of the bread microstructure (ie. 10 to 100 μm), the research mixer is an acceptable tool for modelling the full-size mixer.

Both the full-size and research mixers turn at approximately 360 rpm. This speed is fixed during operation since the mixer rotor and motor shaft are connected by a simple belt pulley arrangement. There is presently no provision for variable speed control. Since the mixers operate to a fixed energy usage criterion, the machinery is instrumented to output the current usage as a function of time. Measurements of current consumption on a full scale mixer are shown in Figure 4 for two different types of impellers: the Turkington, which uses round bars as the helical elements of the blade, and the original Tweedy blade, which is a rectangular cross-section strip bent into a helical shape as seen in Figure 3.

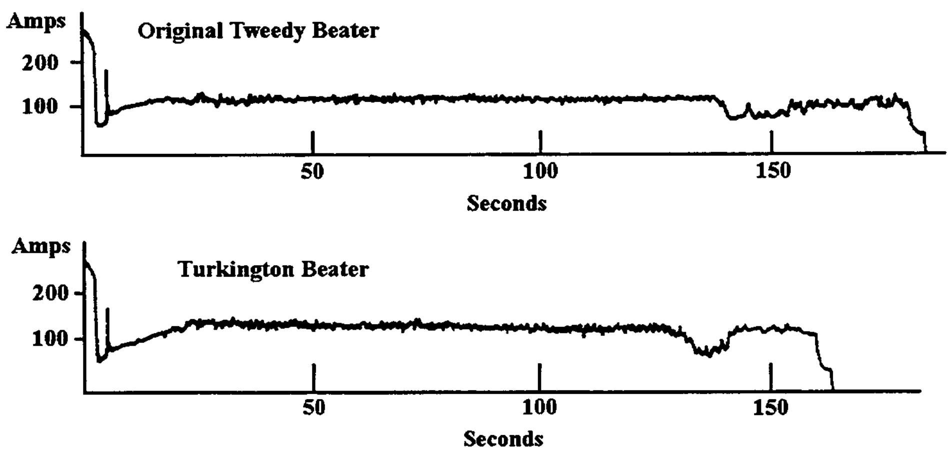

Figure 4: Plot of current consumption for Tweedy and Turkington impeller blades.

The graphs in Figure 4 illustrate the following points:

1. The Turkington blade reaches the end of current consumption in approximately 163 seconds versus 183 seconds for the standard Tweedy blade. This is an 11% improvement in performance.

2. After the initial hydration phase, the Turkington blade reaches a plateau in current consumption that exceeds that experienced by the standard Tweedy blade. This indicates that the round bars of the Turkington beater are meeting more resistance from the dough than the Tweedy beater bars.

3. Towards the ends of the mix cycle, the current level of the Tweedy blade shows some pronounced, but brief, oscillations from the plateau current consumption. There is anecdotal evidence that this behavior is associated with the complex three-dimensional motion of the dough mass which involves vertical displacements into the region above the baffles and impeller.

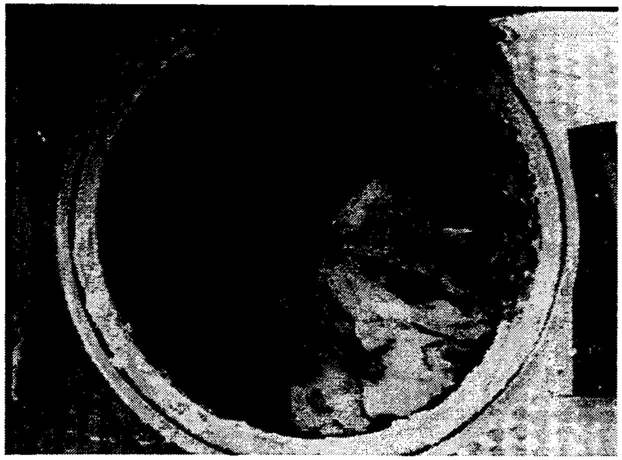

Figure 5: Still frame from the mixing video.

The video tape provided by Goodman Fielder was shot under both normal lighting and stroboscopic conditions. Figure 5 shows a still frame from the tape. The video was considered carefully and viewed frame-by-frame. While the process is highly nonuniform and difficult to follow at normal speed viewing, the following conclusions were reached by the group:

1. The dough mass is very clearly a solid material once the initial hydration phase has been completed. However, some elements of fluid-like behavior are present, and can clearly be seen in the vertical rising of the dough mass up the central spindle. This behavior is typical of rheological flows of high molecular weight fluids and most likely arises from the differences between the radial and circumferential components of the stress tensor.

2. The dough mass can be divided into three distinct radial regions of rotation: interior to the impellers, between the impellers and the interior edge of the baffles, and from the baffle edge to the mixing chamber wall. The material in the central region appears to rotate with the spindle and impeller, while material in between the baffles and impeller may, at times, rotate with a slower speed. The interaction of the dough with the baffles slows the outer edges of the mass relative to the central motion.

3. The motion, as observed through the introduction of a red coloured dough ball, is quite complex and contains significant vertical components as well as the horizontal regions described above.

Any analysis of dough development from a mechanical perspective needs a constitutive law to serve as a framework for the determination of stresses and strains within the material and to gauge strain-rate sensitivity. Phan-Thein *et al.* (1996) have made measurements of the deformation of flour-water mixtures using small samples of approximately 10 grams. They report a strong strain-rate sensitivity and material strains of order 10 associated with peak strengths of the gluten network. Typical failure strains of order 15–20 only slightly exceed the strain levels at peak strength so that the network fails suddenly and with only moderate sensitivity to the rate at which the deformation is applied. This suggests a fixed strain criterion for the modelling of the stretching of the dough mass within the mixing chamber.

The consensus of the study group was that, on the time-scale of impeller rotation, the dough should be considered a solid. However, there remains a strong element of fluid-like behavior on a longer time-scale as indicated by the creep of material up the central spindle and the presence of recirculating three-dimensional flow within the mixing chamber. It was not possible to assess the importance of planar versus three-dimensional material motion from the video tape, and both effects were judged to be of importance.

3. Development within the mixing chamber

A number of parameters and the mechanical phenomena governing development were considered.

3.1 Mixing speed

The development of dough by mechanical means is accomplished through a straining motion in which the gluten molecules are aligned lengthwise so that cross-linking can occur (Moss *et al.*, 1981). The Tweedy mixer rotates at a high rate of 360 rpm in comparison with most other dough mixers as well as other mechanical procedures of bread development. However, the motion within the chamber is highly nonuniform, with material adhering to the central spindle rotating with the angular velocity of the base plate and material on the exterior of the mass constantly impacting the protruding baffles, which act to slow down the edges of the rotating mass.

The efficiency of mixing is a concave downwards function of the impeller speed Ω. For small Ω, the mass will adhere to the spindle and rotate rigidly without significant straining, while for large Ω the impeller will turn so rapidly that it cuts its way through the mass without significant straining except in the material directly adjacent to the impeller blade surfaces. The value of Ω associated with peak efficiency can only be established through an experimental testing programme.

3.2 Strain analysis

An approximate model of two-dimensional stretching is provided by imagining the region between the baffles and the impeller as an area where line elements of the solid are being stretched. One can imagine a "rubber-band" of material with one end looped around the impeller and the other being dragged around the chamber. When the baffle grabs the free end and retards the motion, some strain is inserted due to the differential rotation.

The video tape of the research mixer was analyzed frame-by-frame in order to try and quantify, even approximately, what type of straining might be occurring in the region between the impeller and the protruding baffles. The central spindle and base plate turn with an angular velocity of 6 rev/sec or approximately 40 rad/sec. The exterior of the dough mass is clearly slowed by interactions with the protruding baffles, but this retardation is highly variable.

If we accept an approximate "average" rotation speed of 40 rad/sec for the exterior of the mass, then a line element length of 15 cm, which is attached to an impeller blade at a distance of 10 cm from the center of a 25 cm radius chamber, is subject to a strain rate of order 0.5 per second. This means that within 20 seconds a lineal element would reach an elongation strain of order 10. This prediction clearly overestimates the rate at which strain is imparted to the dough mass, however it illustrates the way in which the differential rotational velocity can stretch the material between the impellers and the baffles.

The exterior of the mass must rotate with an average angular velocity close to that of the impeller, but the situation is complicated by the fact that the deformation motion is three dimensional and the material points on the exterior of the mass continually change. Given the complicated and random nature of the dough mass interaction with the baffles it was felt that further more complicated solid mechanics models would not yield useful information at this point in time.

3.3 The efficiency of the impeller blades

The difference in efficiency between the two blade types (original Tweedy blades with rectangular cross sections versus the Turkington blade with the circular cross section) can be understood in terms of the concentration of stress around rigid bodies which are embedded in a plane of isotropic elastic material with constants Young's modulus E and Poisson's ratio ν.

Figure 6(a) shows a two-dimensional rigid elliptical body with major and minor axes dimensions (a, b) which is subject to a net force F in the minor

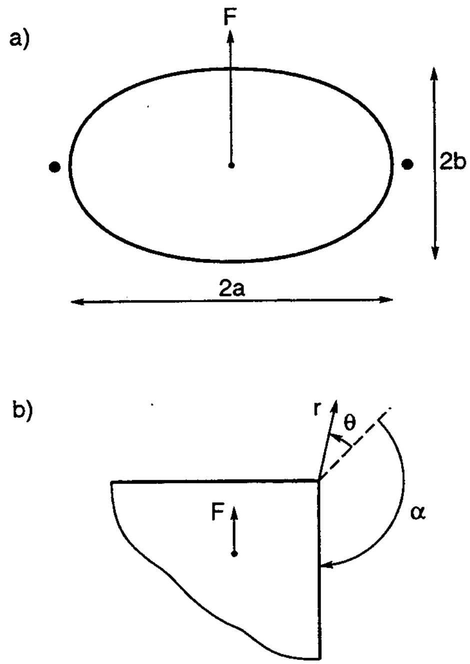

Figure 6: Diagram of (a) smooth body and (b) sharp corner subject to an applied force F.

axis direction. Dimensional analysis shows that the maximum stress in the embedding plane occurs on the interface at the locations marked by the circles and that the stress will have the form

$$\sigma_{max} = \frac{F}{a}\Psi(a/b, \nu)$$

where the dimensionless function Ψ depends upon the aspect ratio a/b and Poisson's ratio ν. For a circular disk-shaped body, the problem of the stress field in the plane can be easily solved by analytic function methods (Muskeleshivili, 1963) and Ψ typically has a value of order 2.5. This geometry is representative of the maximum stresses that occur in the dough surrounding the Turkington impeller blades.

The Tweedy blades with a rectangular cross section produce a very different kind of stress field. The stresses due to a net force F are now concentrated near the sharp corners, which is shown in enlargement in Figure 6(b). This is an example of the well-known singularities that develop near elastic notches. A radial coordinate system (r, θ) is placed upon the corners with the angle θ measured from the bisecting line of the notch of angle α. Buchwald (1965) has shown that the stresses in the near corner region have the form

$$\sigma_{\alpha\beta} = \frac{F}{a} g(\nu) f_{\alpha\beta}(\theta) \left(\frac{r}{a}\right)^{\lambda-1}$$

where g and f are dimensionless functions and the constant λ is the first positive real root of the characteristic equation

$$\sin 2\alpha\lambda + \lambda \sin 2\alpha = 0 \; .$$

For the Tweedy blade, $\alpha = 3\pi/4$ and $\lambda = 0.793$ so that the stresses have a weak singularity at the corner.

The stress concentrations around the corners of the rectangular blade make it easier for the Tweedy blade to cut its path through the dough mass and to sever any gluten strands that have wrapped around the blade. As a result, it takes the Tweedy blade an average of 11% longer to reach the same power dissipation criterion as the Turkington blade.

4. Temperature rise

The vast majority of the energy used by the Tweedy mixer goes into the heating of the ingredients from a starting temperature of 15°C to a finishing temperature of 31°C. A batch of 300 kg of dough consumes approximately 1.23 x 10^7 J of energy based upon the energy usage criterion. The heat capacity of dough is 2750 J/kg and a temperature rise of 15°C requires 1.22 x 10^7 J.

The dominant energy dissipation mechanism in the dough is the temperature rise of the dough with only a small amount of work, say less than 3%, going into useful mechanical development. The slower but more efficient means of mechanical development do a higher proportion of useful work at the expense of more complicated mixing geometries. The solution to the heating problem lies in either improving the design of the existing Tweedy mixer to increase the proportion of useful work, or in living with the current inefficiencies and reducing the temperature of the input ingredients to compensate for the low efficiency of the Tweedy geometry.

Mixing chamber geometries which incorporate some free standing vertical rods or other protrusions for the dough to twist and fold around may increase the proportion of useful work by providing a more effective stretching mechanism, and thereby reduce the overall temperature rise associated with producing a developed dough mass.

5. Recommendations

The Tweedy mixer is an energy intensive and highly nonequilibrium method of developing bread dough. Before significant improvements can be made, a number of specific questions must be answered by further tests with the research mixer.

1. **The role of the baffles.** Clearly the role of the baffles is integral to the stretching of the dough within the mixer. It is suggested that the height of the baffles be extended vertically upward along the walls of the chamber in order to help avoid the problem of a significant portion of the dough mass rising above the central spindle by providing a deflection action back into the center of the chamber. Beyond this immediate change, the effects of depth of intrusion and baffle angle should be explored by modifying the interior of the test mixer to accept baffles of varying geometry. It is important to establish the sensitivity of the development process to the various parameters associated with baffle geometry, and this can only be accomplished through a set of carefully designed experiments.

2. **The importance of the central zone.** The conjecture of the group was that most, but not all, of the material stretching occurs in the region between the impellers and the baffles, and that the central region is associated with some type of recirculation flow around the impeller. If the hypothesis is correct, then the impeller sketched in Figure 7 would be very effective in excluding material from the central region, while still providing blades which could grab the dough mass. The use of a variety of modified base plates to judge the importance of the various regions within the Tweedy mixer is essential to deriving a process that is more efficient in the way that it imparts work on the dough mass.

3. **Adjust the rotational speed of the impeller.** There is no reason to believe rotating the blades at 360 rpm is optimal. A set of experiments with the existing base plate and a variable speed motor may yield data of immediate use. It may very well be that an angular speed cycle can be developed that produces more meaningful work on the dough and avoids excessive heating within the four minute time frame required.

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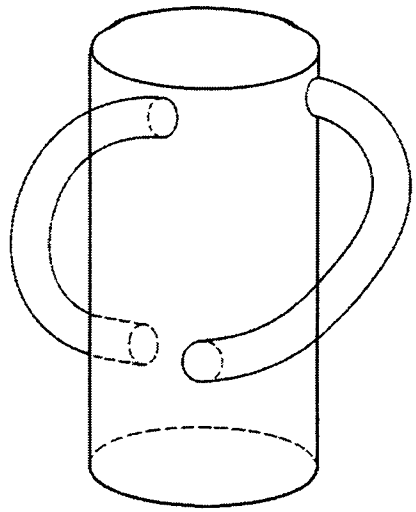

Figure 7: An alternative impeller that excludes material from the central region.

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