

Optimization of rectangular pulp stock mixing chest dimensions using dynamic tests

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ABSTRACT: Agitated pulp chests act as low-pass filters to attenuate high-frequency variability in pulp properties ahead of many pulping and papermaking operations. Dynamic tests made on both industrial and scale-model chests show the complex rheology of pulp suspensions creates deviations from ideal mixing. We determined the dimensions of a rectangular 1:11 scale-model pulp stock chest that provided the best upset attenuation for operation at two fixed chest geometries. The extent of flow bypassing the mixing zone and the effective mixed volume were determined from dynamic tests and used as mixing quality criteria. Optimum chest dimensions differed from those determined using the power required for complete surface motion. The dynamic response sensitivity was reduced substantially for a given chest by the location of the pulp feed and exit.

Application: Consistency control, paper quality, and machine runnability can be increased by reducing the extent of non-ideal flow in pulp stock chests.

The agitation of pulp stock is the most common mixing operation in pulp and paper manufacture. Agitated pulp stock chests serve several purposes. As pulp storage vessels, they permit continued operation during a process upset; when fully agitated they keep stock moving and prevent suspension dewatering. As blend chests, they mix different pulp stocks or pulp suspensions with process chemicals. They reduce temporal process variability by attenuating rapid or high-frequency fluctuations in pulp properties, thus behaving as low-pass filters to complement the action of control loops that only attenuate slower disturbances [1].

Stock chests are most often designed based on proprietary information refined by experience. One common design method, summarized by Yackel [2], matches the momentum generated by the impeller with the momentum required to create motion over the complete surface of the suspension. Ein-Mozaffari et al. [3] studied

pulp mixing in a scale-model (1:11) chest and found stagnant regions existing below the suspension surface [2, 4] even when Yackel's criteria were met. Consequently, both power and impeller momentum flux requirements were underpredicted using Yackel's design criteria.

Chest design often assumes ideal mixing takes place. Hence, mixing dynamics are represented by a first-order transfer function with chest volume selected on the basis of total residence time required by the process [5–7]. In the approach system to paper machines, for example, machine (mixing) chests attenuate disturbances at frequencies higher than the cutoff frequencies of the paper machine control loops. Disturbances not fully attenuated pass through to the process and affect paper quality and machine runnability.

Pulp suspensions are non-Newtonian and have significant yield stress [8–10] that can affect their flow behavior [11, 12]. Non-ideal flows reduce the degree of upset attenuation [13, 14] and

should be considered during chest design [15]. To develop this understanding, Ein-Mozaffari et al. [14] used a dynamic model to identify the type and extent of non-ideal flow in industrial and scale-model chests. Experimental studies examined the effect of operating and chest design parameters such as suspension mass concentration and flow rate, impeller diameter and rotation speed, and location of suspension inlets and outlets. The laboratory studies confirmed that non-ideal flows were common and significantly reduced a chest's ability to attenuate high-frequency variability. The studies also showed small changes in operating conditions dramatically change chest dynamics [11].

Non-ideal flows include short-circuiting (where a portion of the feed flows directly to the exit without entering the mixing zone); recirculation (where a portion of the stock recirculates within the mixing zone); and dead zones (where pulp is stagnant or flows significantly slower than the bulk of the

suspension). Undesirable flows arise from interactions between the circulation patterns generated by the impeller and the suspension flow through the vessel and are dictated, in part, by the chest geometry. Similar results have been reported for industrial chests.

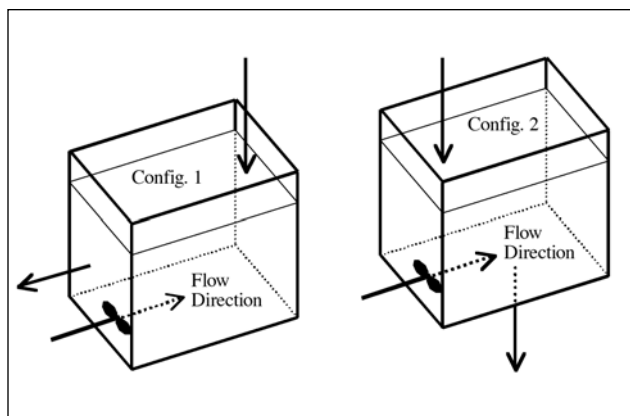
Many observations could be explained by the yield stress of the pulp suspension, which accounts for differences in both suspension mass concentration and other fiber properties (fiber length, fiber type, etc.) [16]. In particular, when the cavern created by the impeller (the region of actively mixed flow determined by the yield stress) approached the pulp outlet, the fraction of flow short-circuiting the mixing zone approached zero. However, yield stress alone could not fully account for the dynamic behavior.

Yackel's [2] criteria for good mixing are based on both the suspension height-to-chest width ratio (Z/W) and the chest length-to-chest width ratio (L/W). Depending on the vessel geometry, optimum stock height is needed to minimize the power required to achieve good mixing. We investigated optimum chest geometry for a 1:11 scale model of an industrial pulp chest using two mixing criteria: (1) the power required to attain complete motion in the vessel including those regions below the suspension surface, and (2) the dynamic response of the chest as determined by the extent of non-ideal flow and the degree of disturbance attenuation.

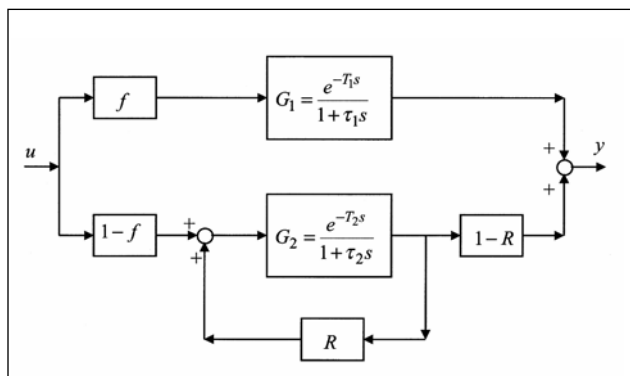
EXPERIMENTAL PROCEDURE

We used a 1:11 geometric scale model of an industrial chest to study dynamic mixing of pulp suspensions. Pulp was pumped from a feed tank, through the mixing chest, and then to a discharge tank. The chest was rectangular (width, fixed at $W = 40$ cm; length, variable at $L = 40, 53$, and 65 cm; and stock height, variable up to $Z = 70$ cm) and equipped with a 16.5-cm-diam. Maxflo side-entering impeller (Chemineer Inc., Dayton, Ohio). Two sets of chest geometries were tested (**Fig. 1**). Changes in suspension height were measured over the range $Z/W = 0.75$ – 1.63 at a fixed L/W of 1.32. Changes in chest length were measured at $L/W = 1.00, 1.32$, and 1.75 for a fixed Z/W of 1.25. The impeller speed was varied from 300–1750 rpm and the suspension flow from 7.9–37.1 L/min. Suspension flow was changed to keep the nominal residence time (V/Q) constant at 804 s for all tests. Details of the experimental apparatus are provided in [3].

The chest's dynamic response was quantified using a dynamic model that incorporated non-ideal flows observed in industrial and scale model chests. The model allowed for two parallel suspension flow paths through the chest: (1) a mixing zone and (2) a short-circuiting (a channeling or bypass) zone. A frequency-modulated random binary input signal, which concentrated energy at the frequencies the chest was designed to attenuate, governed injection of saline solution



1. Flow configurations studied. Configuration 1 is commonly used in industry.



2. Continuous-time dynamic model of pulp mixing chest.

into the pulp feed. The conductivity of input and output pulp streams was measured using flow-through conductivity sensors. The data were used to identify the parameters of the dynamic model, whose transfer function in the continuous-time domain is given by Eq. 1 [14]:

$$G_{chest} = \frac{f e^{-T_1 s}}{1 + \tau_1 s} + \frac{(1-f)(1-R) e^{-T_2 s}}{1 - \frac{e^{-T_2 s}}{1 + \tau_2 s}} \quad (1)$$

Figure 2 shows a block diagram of the model, where f is the fraction of pulp feed bypassing the mixing zone. The fraction of flow exits the mixing chest at a time interval T_1 and is mixed as allowed by a first-order transfer function with time constant τ_1 . The remaining flow stream enters the mixing zone around the impeller, is delayed in exiting the chest by an interval T_2 , and is mixing according to a first-order

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transfer function with time constant τ_2 . Some pulp in the mixing zone recirculates (R), although tests have shown the fraction of pulp recirculating is close to zero. Based on this model, an ideal dynamic response occurs when short-circuiting and recirculation approach zero (i.e., $f \rightarrow 0, R \rightarrow 0$) and the time constant for the mixing zone approaches the nominal time constant for the system, V/Q , where V is the suspension volume and Q is the pulp flow rate.

To estimate the model's parameters, input-output data from the dynamic tests were subjected to a numerical procedure developed by Kammer et al. [17]. Two of the model parameters were used to indicate the quality of mixing measured in the system: (1) the degree of short-circuiting in the vessel, f , and (2) the effective volume of suspension mixed compared with that of an ideally mixed vessel with vessel volume, (V_{mixed}/V) . To calculate this ratio, the effect of recirculation was eliminated ($R = 0$) [11, 12], giving Eq. 2:

$$\frac{V_{mixed}}{V} = \frac{Q\tau_2(1-f)}{V} \quad (2)$$

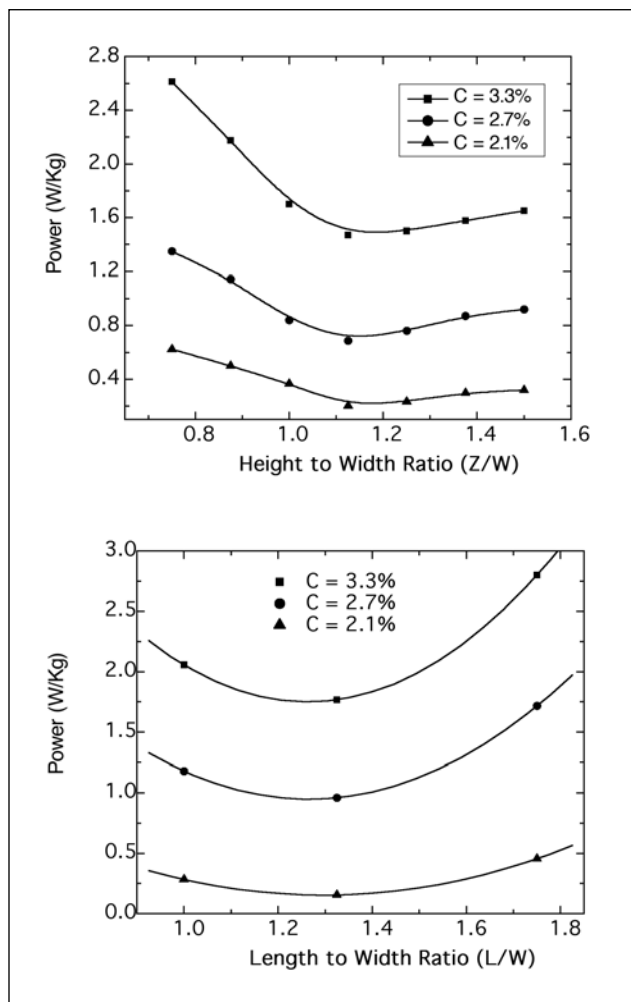
For ideal mixing, $f = 0$ (no bypassing) and $V_{mixed}/V = 1.0$ (all the suspension volume involved in mixing). Hardwood bleached kraft pulp with a fiber length of 0.90 mm and suspension mass concentration varying from 2.1%–3.3% was used in the tests. We also tested the effect of pulp feed and exit locations for two configurations shown in Fig. 1. Configuration 1 is the common industrial configuration (due to the ease of fabrication and maintenance), while Configuration 2 is designed to have better mixing characteristics (although it is not used industrially).

RESULTS AND DISCUSSIONS

Yackel [2] specifies the optimum dimensions for rectangular agitated pulp chests by determining the minimum power needed to provide complete motion in the chest. Yackel defines "complete motion" as suspension motion over the entire upper surface of the mixing vessel. We refer to this as "complete surface motion" because stagnant regions may exist below the pulp surface. Yackel's findings, summarized in

L/W	Z/W
0.8 – 1.0	0.55
1.25	0.6
1.5	0.8
2.0	0.9

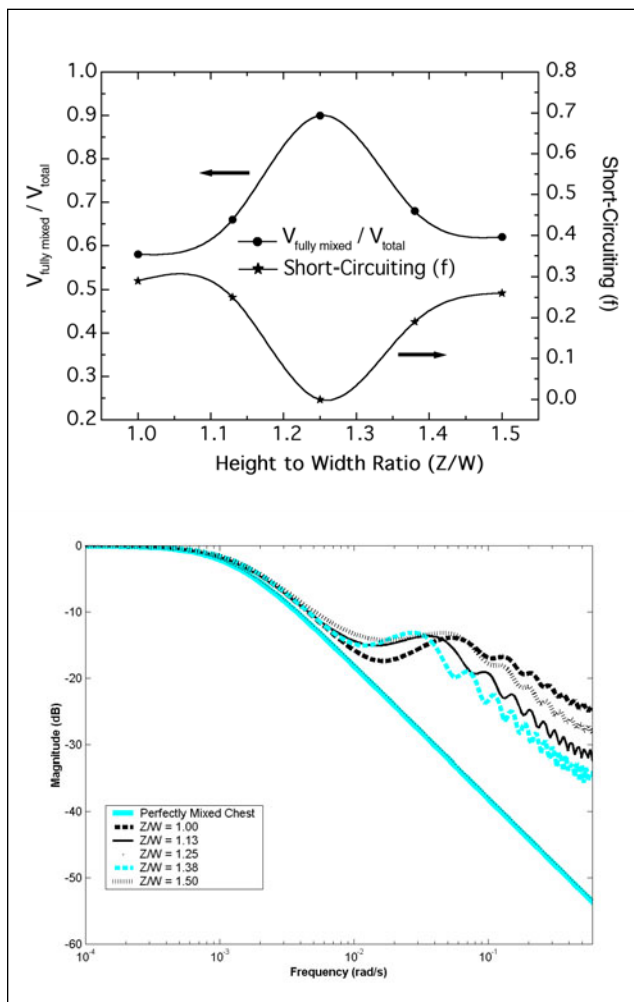
1. Yackel's optimum rectangular chest geometry [2].



3. Power required for complete motion vs. (a) suspension height-to-chest width ratio (Z/W) for $L/W = 1.32$ and (b) chest length-to-chest width ratio (L/W) for $Z/W = 1.25$.

Table I, show that as the aspect ratio (L/W) of the chest increases, the optimum height at which the vessel exhibits complete surface motion increases. However, Yackel also states that the minimum power for agitation occurs when the chest is cubic (i.e., $L/W = 1$ and $Z/W = 1$), which disagrees with the design data.

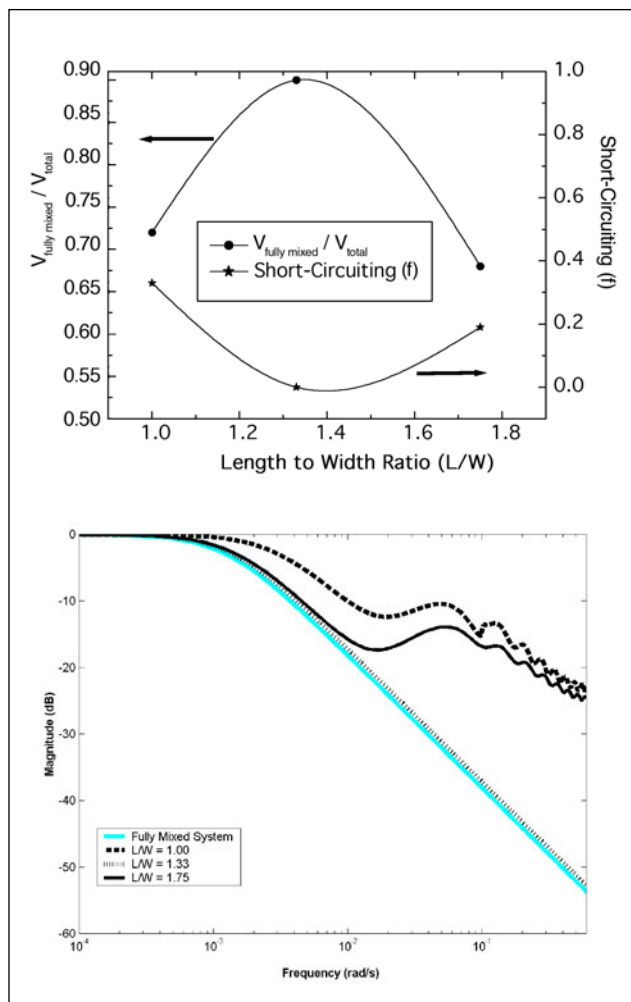
We determined the minimum power required to create complete motion (assessed visually) throughout the vessel, including in the corners below the suspension surface to avoid stagnant regions, for the 1:11 scale-model chest operated in batch mode for two conditions: (1) where L/W was fixed at 1.32 and (2) where Z/W was fixed at 1.25. **Figure 3a** shows the effect of suspension height on the power required to achieve complete motion at three fiber mass concentrations. Power decreases as Z/W increases from 0.75, reaching a minimum at $Z/W = 1.13$. As the suspension height



4. Effect of suspension height-to-chest width ratio (Z/W) for $L/W = 1.32$ for configuration 1 on (a) the extent of fully mixed volume and short-circuiting and (b) upset attenuation.

(Z/W) increases further, the power required for complete motion increases, but only minimally. The optimum suspension height is not a function of fiber mass concentration over the range of 2.1%–3.3%. **Figure 3b** plots the power required for complete motion as a function of chest length-to-chest width ratio (L/W) for a fixed suspension height ratio of $Z/W = 1.25$. As shown, the optimum L/W ratio for the scale-model chest is approximately 1.3 and again is not a function of fiber mass concentration.

Interpolating Yackel's data (for the complete surface motion criteria), we obtain minimum power for $L/W = 1.32$ at a Z/W of approximately 0.65, much lower than the value of $Z/W = 1.13$ found using the more stringent requirement of complete suspension motion in the vessel. A similar situation is found when the suspension height is fixed so that $Z/W = 1.25$. Here, extrapolation of Yackel's data would give a value of



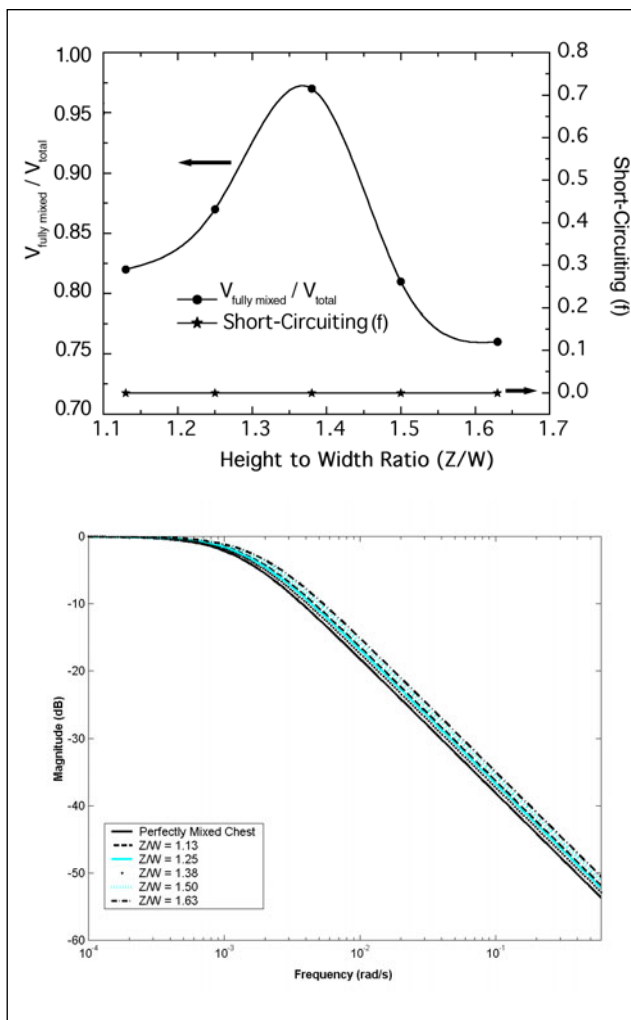
5. Effect of chest length-to-width ratio (L/W) for $Z/W = 1.25$ for configuration 1 on (a) the extent of fully mixed volume and short-circuiting and (b) upset attenuation.

around $L/W = 2.7$, double the value of 1.3 determined here.

Given that optimum dimensions for achieving good mixing seem to depend on the criterion of mixing quality chosen, we examined criteria based on the approach to perfect mixing as measured in dynamic tests. Identical geometrical conditions were used for each test. The extent of short-circuiting (f), the fraction of chest volume ideally mixed (Eq. 2) and the dynamic response (as determined using a Bode plot) were used to characterize mixing quality. For these tests, hardwood pulp with a mass concentration of 3.3% was used with the nominal time constant kept constant at 804 s. The specific power for agitation was maintained constant at 2.9 W/kg for all tests, which ensured that for all tests the suspension was in complete motion.

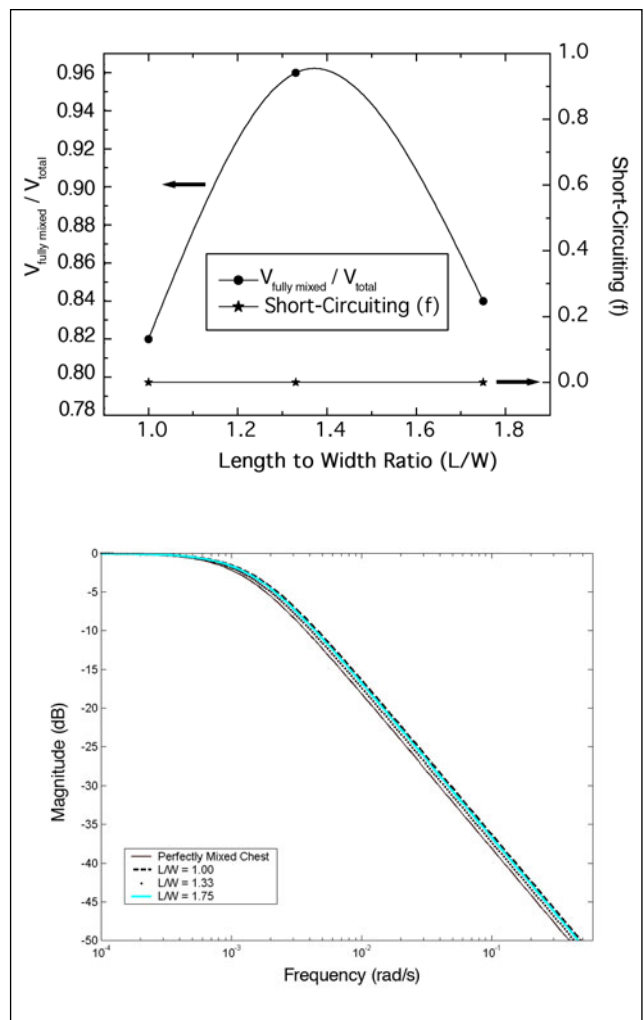
The effect of suspension height-to-width ratio (Z/W) on the fraction of fully mixed volume and short-circuiting for

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6. Effect of suspension height-to-chest width ratio (Z/W) for $L/W = 1.32$ for configuration 2 on (a) the extent of fully mixed volume and short-circuiting and (b) upset attenuation.

Configuration 1 is shown in **Fig. 4** for an L/W of 1.32. Using our dynamic mixing criteria, the maximum fully mixed volume and minimum short-circuiting occur at $Z/W = 1.25$ (**Fig. 4a**). At other Z/W ratios the extent of short-circuiting and the volume of suspension not involved in active mixing (1 minus the dead volume) increases, although the specific power applied (2.90 W/kg) was, in all cases, higher than that required to create complete motion in the vessel. These data support the observation that non-ideal flow is not eliminated when complete motion is achieved in the pulp suspension [16]. **Figure 4b** gives the amplitude Bode plots showing the disturbance attenuation as a function of Z/W for $L/W = 1.32$ for Configuration 1. The attenuation provided by scale-model chest at $Z/W = 1.25$ approaches that of a perfectly mixed chest (which has a simple first-order transfer function) while the degree of variability re-



7. Effect of chest length-to-width ratio (L/W) for $Z/W = 1.25$ for configuration 2 on (a) the extent of fully mixed volume and short-circuiting and (b) upset attenuation.

duction at other Z/W ratios departs from the ideal. Similar tests were made with Z/W fixed at 1.25 with L/W changed. **Figure 5a** shows that f is minimized and V_{mixed}/V maximized when $L/W = 1.33$. Again, the Bode plots confirm that for this configuration chest dynamics approach that of an ideally mixed vessel (**Fig. 5b**). These results show that both Z/W and L/W significantly affect the performance of the chest when acting as a low-pass filter.

Dynamic testing of industrial and scale-model chests have shown that pulp feed and exit locations significantly affect performance of agitated pulp chests [11, 14, 16]. Hence, we investigated the optimum chest dimensions for a set of input and output locations (Configuration 2) shown previously to give superior mixing response. The same conditions described previously were used with the effect of Z/W ratio

		Mixing Criteria			
Test Conditions	Parameter	Complete Surface Motion Yackel [2]	Complete Motion	Dynamic Response	
				Config 1	Config 2
$L/W = 1.32$ $Z/W = 1.25$	Z/W L/W	0.65 2.7	1.1 1.3	1.25 1.3	1.38 1.35

II. Comparison of optimal rectangular chest geometries by criteria.

for $L/W = 1.32$ shown in **Fig. 6** and the effect of L/W for $Z/W = 1.25$ shown in **Fig 7**. Note that while Configuration 1 was prone to a high degree of short-circuiting, that Configuration 2 eliminated this ($f = 0$ for all cases). As an explanation, in both configurations the impeller pushes the suspension toward the opposite wall, moves it from the bottom to the top along the far wall, and then returns it along the suspension surface to the impeller suction. In this flow, Configuration 1 (where pulp is added on the suspension surface near the wall opposite the impeller) enables a large percentage of feed to be conveyed directly to the exit location without being drawn into the mixing zone. In Configuration 2, however, the feed is forced to flow through the mixing zone before leaving the chest.

Using the maximum mixed volume as a criteria for chest dimensioning leads us to conclude that for Configuration 2, for $L/W = 1.32$, the optimum suspension height is given at about $Z/W = 1.38$ (Fig. 6a); for $Z/W = 1.25$ the optimum chest length-to-width ratio is about $L/W = 1.35$. In both instances, the Bode plots confirm these ratios give the best dynamic response but the changes in dynamic response with chest geometry are not as dramatic as that for Configuration 1. Any loss in attenuation is due to the marginally reduced active mixing volume.

A comparison of the optimum chest dimensions found for the two tests series ($L/W = 1.32$ and $Z/W = 1.25$) conducted are summarized in **Table II**. For both cases, the use of different quality criteria yields different

optimum chest dimensions. First, we note the criteria of "complete surface motion" used by Yackel gives markedly different results from the other mixing criteria examined. The fact that Yackel states in his text that a cube gives the minimum power use contradicts the data presented in his monograph and creates uncertainty as to what the best dimensions really are [2]. However, in both instances, Yackel's values differ from those found using "complete motion" or "optimum dynamic response" as mixing quality indicators. Indeed, these indicators yield optimum chests that are not too far from cubic configurations.

Within the accuracy of the method used, the optimum dimensions found for Configurations 1 and 2 are the same. However, while departures in chest dimensions for Configuration 1 create dramatic changes in the dynamic response of the system (Figs. 4b and 5b), they do not create significant changes for the dynamic response in Configuration 2 (Figs. 6b and 7b). In industrial operations, where the suspension height may change with operating conditions, chests such as Configuration 1 (as most industrial chests are) will experience dramatic changes in system dynamics that depend on the chest's suspension height. Because these chests often are used as buffers, their level is generally not tightly controlled. Indeed, significant work has gone into development of average level controllers that purposely let tank level fluctuate between two extreme values. Although such control provides optimal buffering, it can be detrimental to mixing performance.

In chests such as Configuration 2, however, much smaller changes in system dynamics would occur and hence more stable operation would ensue. This is just one more indication that system dynamics are dramatically affected by the location of the inlet and outlet ports in a mixed vessel.

Determination of optimum chest dimensions using this procedure is time consuming so we investigated only a small subset of the possible chest dimensions and operating conditions. A more efficient method is needed to examine a wider range of operating conditions, in particular the optimization of feed and exit locations in existing chests. We are investigating computational fluid dynamics (CFD), which has strong potential in this area, and when verified with selected confirmatory tests may greatly improve ability to develop design criteria.

CONCLUSIONS

Rectangular, agitated, pulp stock chests have been designed to achieve complete surface motion in the vessel. However, dynamic tests show pulp mixing can be far from ideal even when complete motion is achieved. Thus, the quality of mixing and hence optimum chest dimensions depends on using either the extent of non-ideal flow or the degree of upset attenuation. Also, pulp input and output locations significantly affect the dynamic behavior of a pulp chest and must be considered during design. **TJ**

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NOMENCLATURE

C	fiber mass concentration, %
D	impeller diameter, m
f	percentage of short-circuiting, (fraction)
G	transfer function
L	chest length, m
N	impeller speed, rpm
Q	pulp flow rate, m ³ /s
R	percentage of recirculation, (fraction)
T	time delay, s
V_{mixed}	fully mixed volume, m ³
V	suspension volume inside the mixing chest, m ³
W	chest width, m
Z	suspension height, m
τ	time constant, s

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INSIGHTS FROM THE AUTHORS

Pulp mixing often takes place in stock mixing chests for which design and operation have been based on proprietary information. Our earlier work, in the laboratory and in industry, showed stock mixing chests have significant non-ideal flow, including short-circuiting and formation of dead zones. We wanted to determine the effect of chest dimensions on the quality of mixing, as measured using dynamic tests, so chest dimensions can be optimized. We found the dimensions for a rectangular chest to be different from those recommended in the literature.

Mixing dynamics testing is time consuming, and obtaining the parameters for evaluating dynamic mixing quality relies on a black-box model for analysis. We choose two parameters: the ratio of fully mixed suspension volume to the vessel volume, and the extent of disturbance attenuation.

The dramatic changes in mixing quality that can occur with very small changes in chest design and operation reconfirmed the importance of pulp feed and exit locations in achieving good mixing. Mills can improve the mixing dynamics of existing chests by optimizing suspension height. Other operating changes can reduce non-ideal flows. Ahead of a paper machine, improved mixing can improve consistency control and subsequently increase paper quality and machine runnability.



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We are developing tools to model mixing, including computational fluid dynamics (CFD). Advanced experimental techniques including particle image velocimetry (PIV) in model fluid systems and electrical resistance tomography (ERT) to measure cavern size in pulp suspensions will help us better understand mixing. Rectangular and cylindrical chests (including the reduced bottom chests used for mining high-density storage towers) are being studied and new techniques are being developed to measure and quantify mixing quality in the mill.

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