HYDRAULIC SIMILARITY OF HEADLOSS PREDICTIONS DERIVED USING COMMONLY USED METHODS VERSUS ACTUAL RESULTS AS IT RELATES TO WASTEWATER SCREEN ELEMENTS

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ABSTRACT

Experience has shown the predictive reliability of two commonly used equations for the prediction of headloss (known as the Bernoulli principle and the Kirschmer method) may be questionable under certain conditions, especially at higher flow velocities through fractional openings. To quantify this observed disparity, a series of tests were executed to compare predicted headloss—employing the results of both these equations—to actual results under controlled conditions. Test results indicate that the headloss predicted by the Bernoulli principle consistently overstates actual headloss through screens by a significant amount. The Kirschmer method correlated much closer to actual headloss, however it proved to be less than satisfactory for some openings or bar shapes. Study of the results of these tests, along with careful examination of the two equations, indicate that better correlations for headloss prediction versus actual measured values could be obtained by modifying elements of both the Bernoulli and Kirschmer equations, or by applying Computational Fluid Dynamics (CFD).

KEYWORDS: Kirschmer, Bernoulli, preliminary treatment, screens, headloss, approach velocity, solids capture, blockage, Computational Fluid Dynamics (CFD).

INTRODUCTION

Two important equations dominate the mathematics of headloss prediction. These are the Bernoulli principle, first described in *Hydrodynamica*, published in 1738, and the Kirschmer method, first published in 1926 in *Untersuchungen uber den Gefallsverlust an Rechen*. Neither of these fluid dynamic formulas were developed specifically for use in the prediction of headloss relative to wastewater screens though they have served the industry adequately in the past. Deviations from actual have been noted when these formulas are applied to screens with smaller openings (< 25 mm or 1 in.) in the presence of higher flow velocities. With preliminary wastewater screening trending toward smaller openings, it is necessary to improve the accuracy of headloss prediction as experience demonstrates that neither Bernoulli nor Kirschmer are reliably predictive at higher flow velocities through fractional openings. This has significant implications in the performance of wastewater screens as under or overestimating headloss can potentially result in screens operating outside commonly accepted ranges, which could lead to solids carryover (thus inefficient screening affecting downstream processes), and under or over designing the elements associated with a plant's screening system. Inaccurate estimations of headloss can also generate several operations and maintenance (O&M) problems at the plant ranging from problems with the actual screening equipment due to solids deposition before the screens, to O&M issues associated with solids carryover, such as the clogging of pump impellers, mixer malfunctioning due to ragging, reduced membrane performance, as well as other negative impacts.

It is the purpose of this paper to provide the results of a series of tests of actual headloss generated in such a method that the results could be compared directly with the headloss predicted by both the Bernoulli principle and the Kirschmer method. In addition, this paper will suggest that better correlations for headloss prediction versus actual measured values may be obtained by modifying elements of both the Bernoulli and Kirschmer equations. Suggested changes to the coefficients in these equations will be provided for openings of 6mm [0.25 in.], 13mm [0.5 in.], and 19mm [0.75 in.] as well as for trapezoidal, teardrop, and rectangular shaped bars installed in screens with each of the three opening sizes.

METHODOLOGY

In order to validate the differences between actual headloss in a wastewater screen and the predictions generated by either the Bernoulli or Kirschmer methods, an experimental test channel was constructed. Subsequently, a series of tests were performed with different screen geometries and different approach velocities, and the actual headloss through each configuration was recorded. The experimental results were then compared to the predicted results by the two methods outlined. Additionally, a limited number of Computational Fluid Dynamics (CFD) runs were performed to compare the model headloss results with actual data.

SETUP

A channel was constructed of smooth painted carbon steel with a width of 305 mm [12 in.], a depth of 915 mm [36 in.], and a uniform length of 2438 mm [96 in.]. This channel was placed on top of a reservoir with two chambers separated by a partition which functioned as an overflow weir for calculation purposes. Water was drawn out of the first chamber by the custom low head, high volume pump assembly and allowed to fill the test channel, then spilled over into the second chamber. This water then flowed over the interior partition into the first chamber allowing continuous operation. An adjustable overflow weir was utilized at the end of the channel to more readily control flow, and the channel was hinged at the inlet end to allow slope changes. Screens with 6 mm [0.25 in.] wide bars were employed with spacing (clear openings) of 6 mm [.025 in.], and were made of three distinct bar geometries: trapezoidal, rectangular, and teardrop. The screens were inclined from horizontal by 60 degrees and captured by a steel track approximately 5/8 of the way down the channel length. The channel was mounted above a 915 mm [36 in.] x 915 mm [36 in.] x 4267 mm [168 in.] steel tank. In this tank were two compartments separated by an overflow weir. As water flowed from one compartment to the other head would build over the weir allowing flow measurements to be taken. Water was pumped up to the channel with a 330mm [13 in.] axial flow pump. Once water flowed through the channel it was allowed to fall back into the tank to be re-circulated through the pump and back into the channel. Flow rates of 170 liters/second [6 cfs] were achieved through this test setup. Flow conditions were maintained at sub-critical levels upstream of the screen.

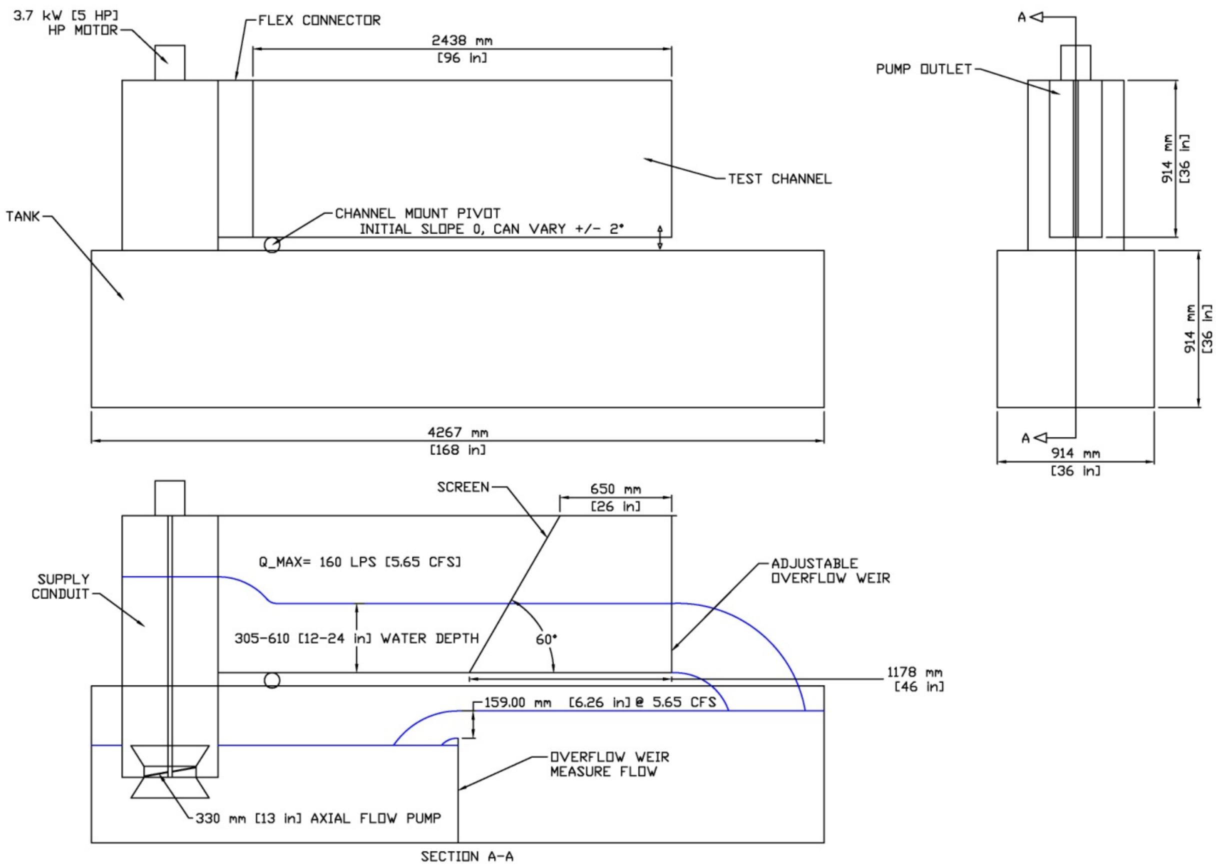


Figure 1. The test channel was placed on top of a reservoir with two chambers separated by a partition which functioned as an overflow weir for calculation purposes.

Figure 2. Side view of test setup.

Figure 3. End view of test setup.

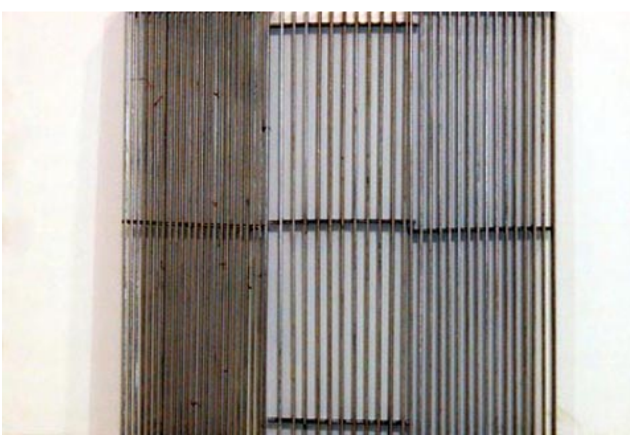


Figure 4. Nine screens (3 openings, 3 bar shapes) were used in this test series.

TEST 1 - HEADLOSS TEST

The adjustable weir was set to overflow at 305 mm [12 in.] above the channel's invert. Flow conditions were maintained sub-critical both upstream and downstream of the screen in the channel. Water delivered to each of the 9 test screens while recording flow, upstream depth of water, and downstream depth of water. Next the same was repeated with a 152 mm [6 in.] weir installed, downstream of the screen.

TEST 2 – CONFORMATION TEST

Each screen was installed then a flow rate was delivered to the screen. The weir was then adjusted until the upstream water level was near the top of the screen. This data point was recorded for openings of 6mm [0.25 in.], 13mm [0.5 in.], and 19mm [0.75 in.] for trapezoidal, teardrop, and rectangular shaped bars. Each time the weir was lowered upstream water depth, downstream water depth, and flow were recorded.

TEST 3 - CAPTURE RATE TEST

The 6 mm [0.25 in.] trapezoidal, 6 mm [0.25 in.] teardrop, and 6 mm [0.25 in.] rectangular screens were installed and initially a flow rate was delivered to the screen. The weir was then adjusted until the upstream level was near the top of the screen. In each case 100 solid particles were added upstream of the screen. The solid particles consisted of cotton fabric cut into 6 x 25 mm [.025 in. x 1 in.] pieces. A mesh cover was fastened in the returning water to catch passed solids. The weir was varied to produces flow conditions at several head losses. The flow was stopped after each flow condition and solids were counted as captured by the screen and mesh.

BASIS OF TESTING

Tests for different screen configurations were performed and the actual headloss was compared against the predicted headloss based on the Bernoulli and Kirschmer methods.

For the purposes of this paper, the following equations were used for Bernoulli and Kirshmer

(From Manual of Practice No. 8, 2009)

Bernoulli:

$$h = \frac{(V^2 - v^2)}{C \cdot 2g} \qquad \text{(Equation .1)}$$

Where,

h	=	headloss, m (ft);
V	=	velocity through bar screen, m/sec (ft/s);
v	=	velocity upstream of bar screen, m/sec (ft/s);
g	=	gravitational acceleration, 9.81 m/s^2 (32.2 ft/sec^2); and
C	=	friction coefficient (0.7 clean screen).

Kirschmer:

$$h = \beta\,(w/b)^{1.33} h_v \sin ø \qquad (11.2)$$

Where,

h	=	headloss, m (ft);
β	=	a bar shape factor (Table 11.2);
w	=	maximum cross-sectional width of bars facing upstream, m (ft);
b	=	minimum clear spacing of bars, m (ft);
h_v	=	upstream velocity head, m (ft); and
ø	=	angle of bar screen with horizontal.

Common differences between the two methods are outlined in Table 1 (below).

Bernoulli	**Kirschmer**
Does not differentiate between bar shapes	Modeling blinding of screens is not straightforward
Does not include the screen angle as a function of the headloss directly	Ignores the downstream hydraulic conditions

TABLE 1. Common differences between the two methods

TEST RESULTS

Figures 5 through 13 show the results of the headloss testing, (Test 1), for the different screen configurations (6 mm [0.25 in.], 13 mm [0.50 in.], 19 mm [0.75] in each with a different bar type trapezoidal, rectangular, teardrop).

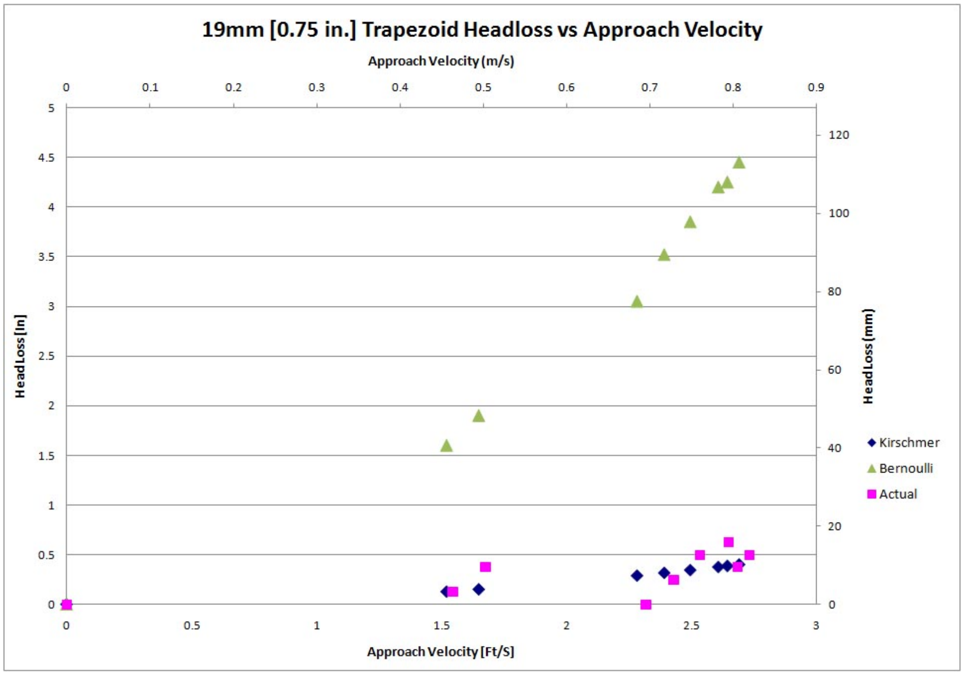
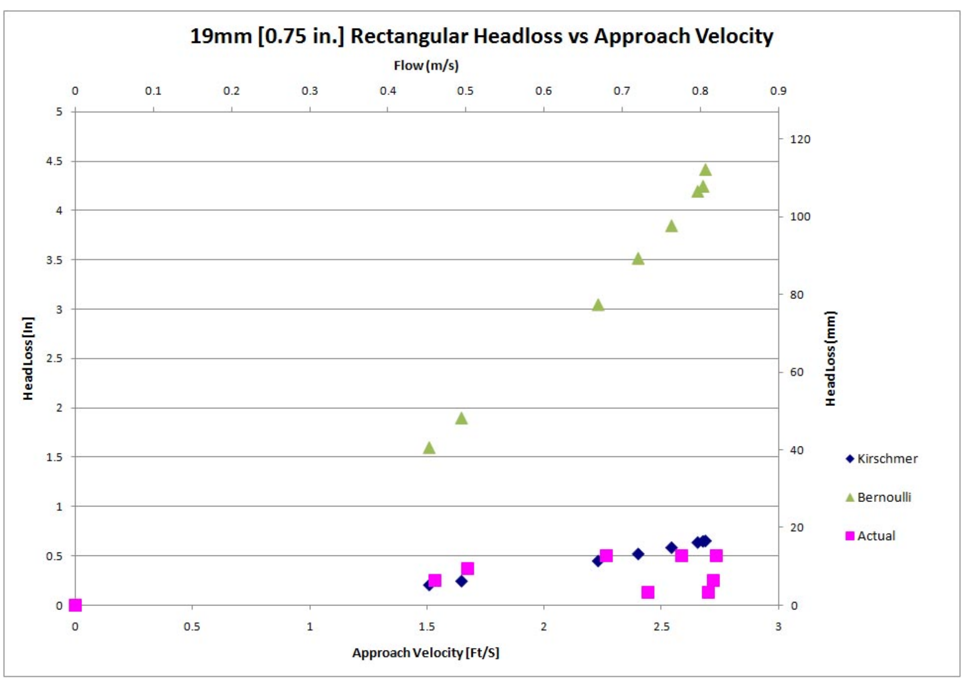


Figure 5.



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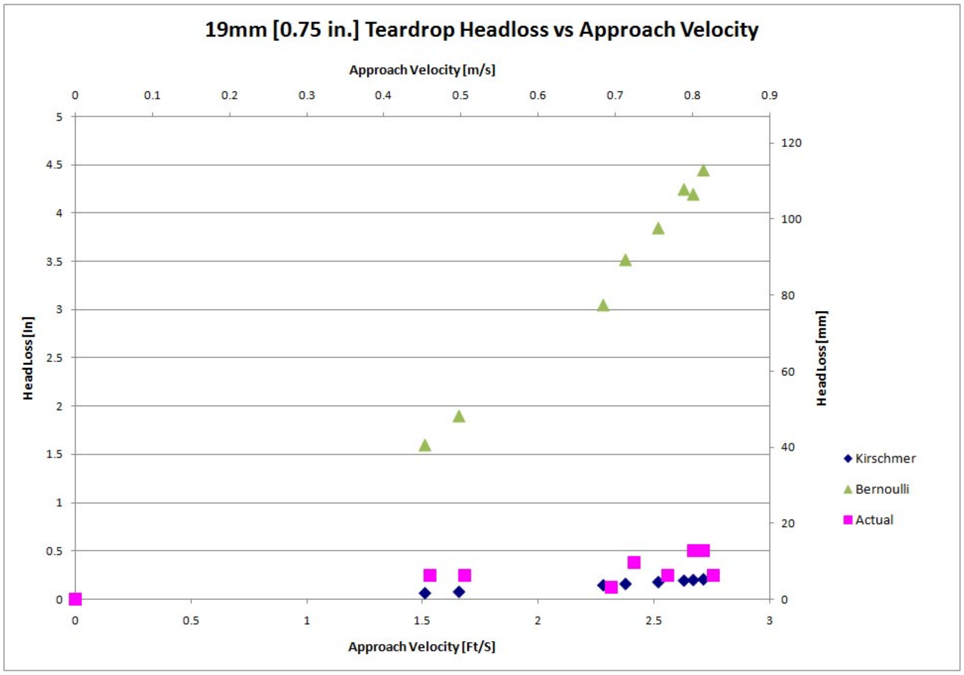

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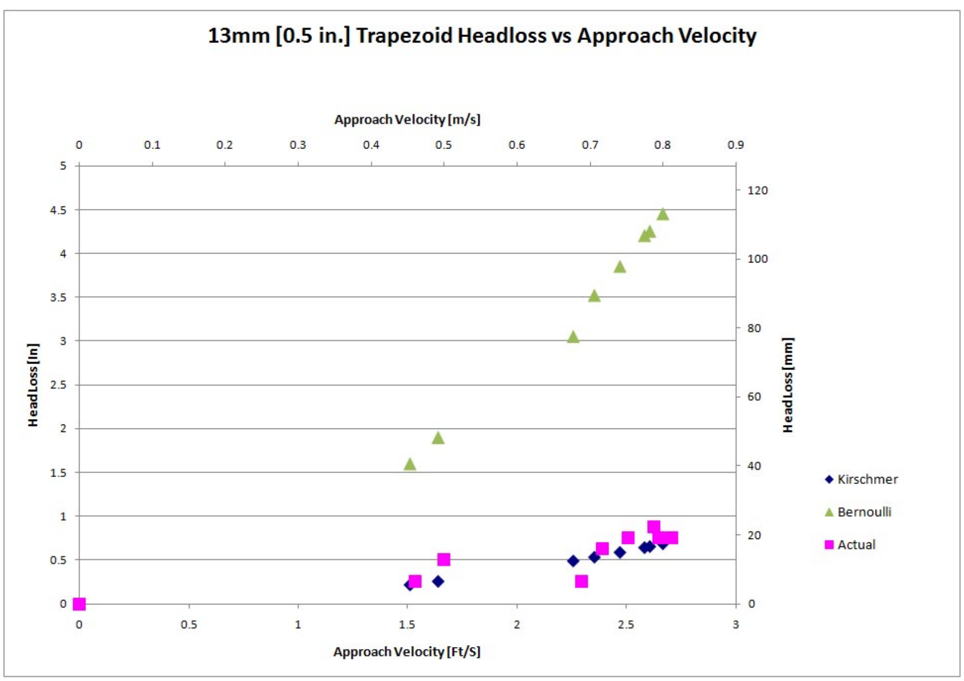

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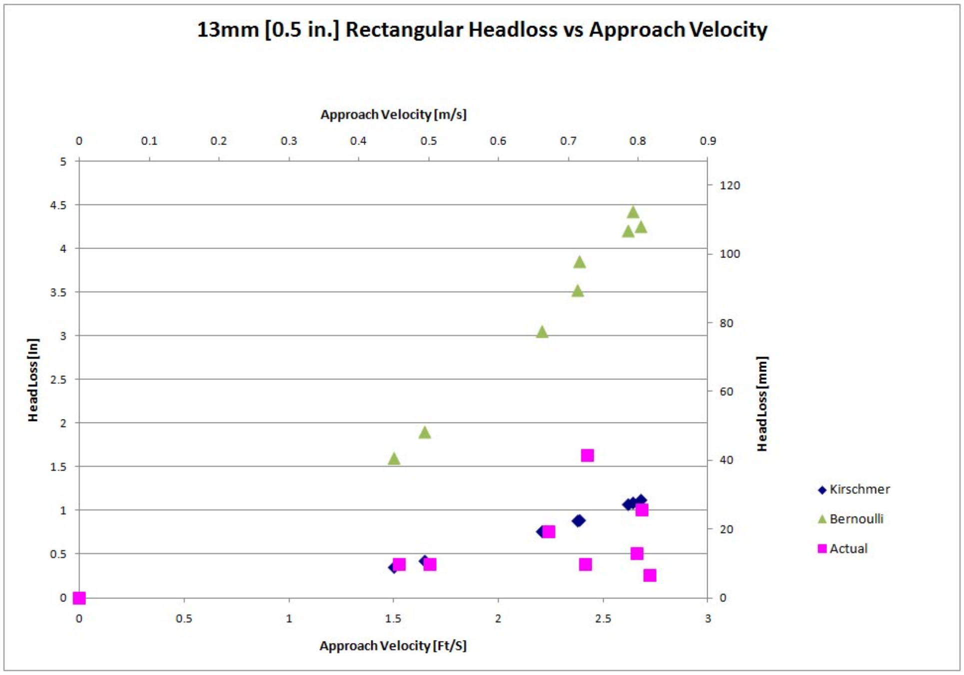

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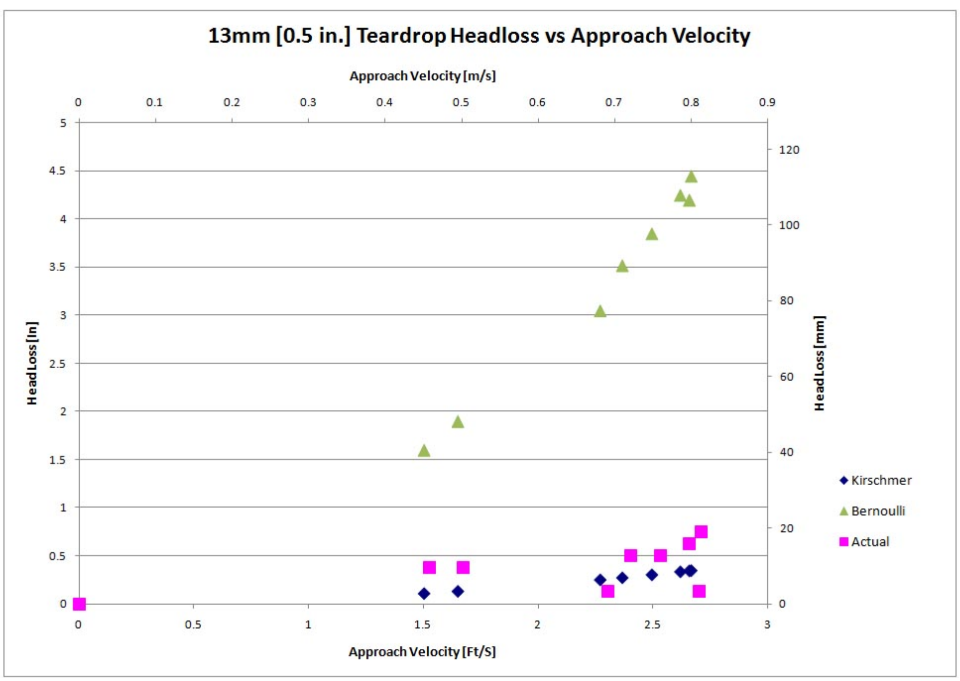

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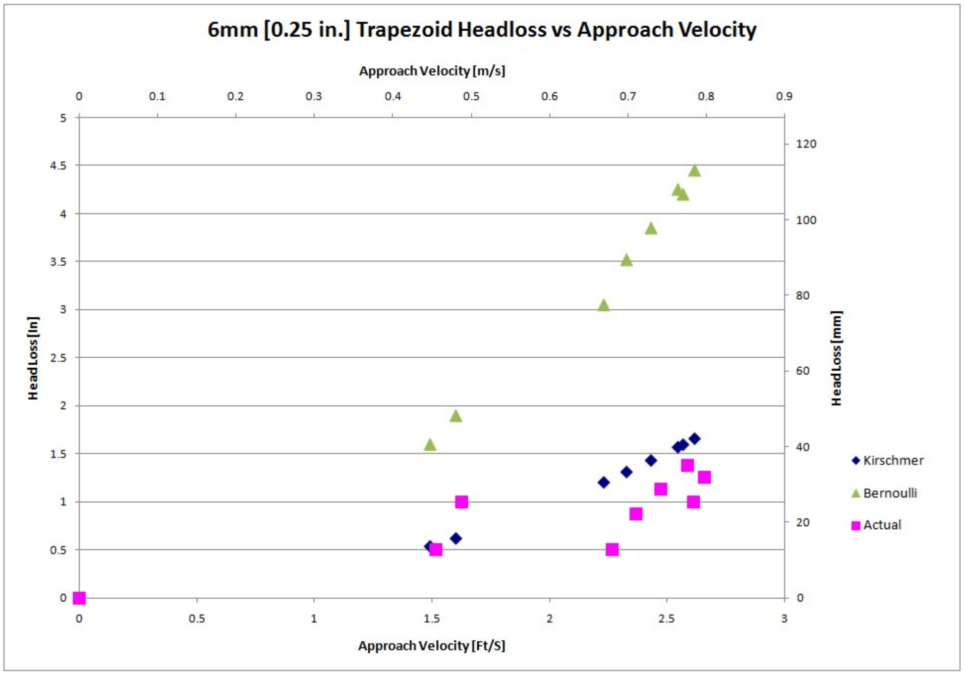
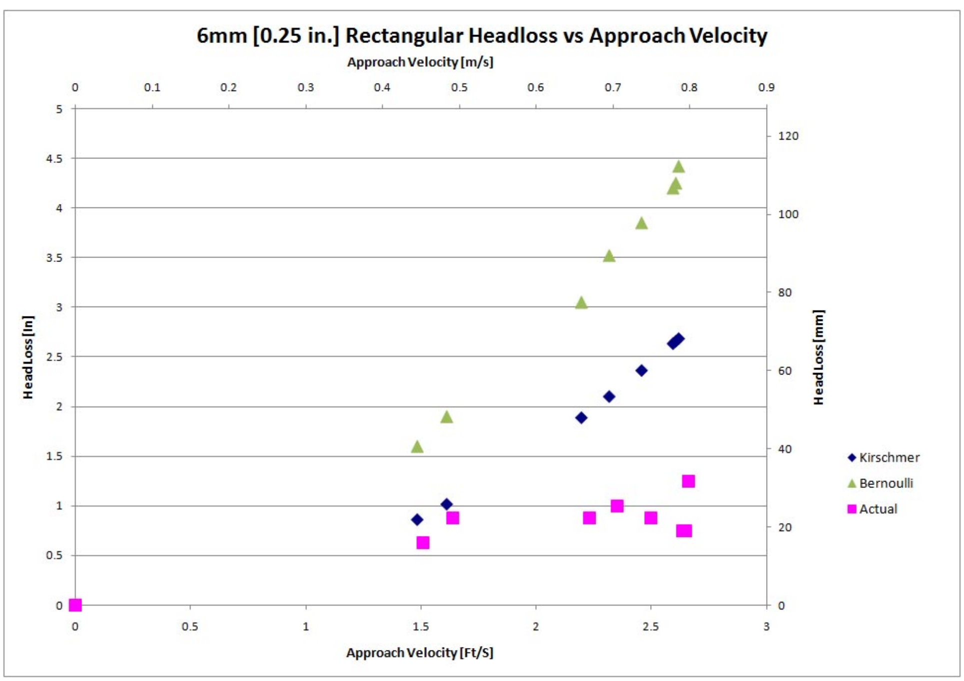


Figure 11.



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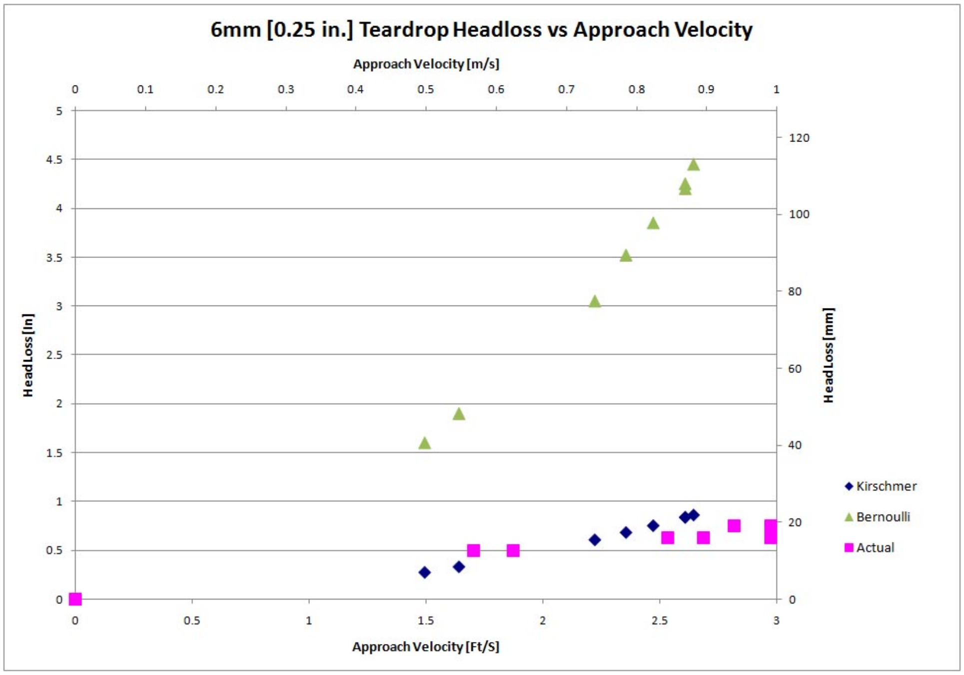


Figure 13.

From figures 5 through 13, the following conclusion can be made:

1. All of the Figures show that headloss predicted by the Bernoulli equation (with the standard C coefficient of 0.7) consistently overestimated the actual headloss through the screens by a significant amount.
2. The Kirschmer prediction with commonly used β coefficients of 0.76 for teardrop, 1.5 for trapezoidal, and 2.42 for rectangular; correlated much closer than Bernoulli in general terms. However, as seen in some of the Figures this correlation is not satisfactory for all openings or bar shapes.
3. Figures 5 through 13 conclusively indicate that the current screen headloss prediction methods are not accurate.

DISCUSSION

The project team decided to investigate if better correlations for headloss prediction versus actual measured values could be obtained by modifying elements of the Bernoulli and Kirschmer equations. Thus, through trial and error the C and β coefficients were modified to establish a better match. Table 2 shows the revised coefficients for providing more reasonable match between the actual headloss with the predicted headloss curve for the proposed C coefficient.

Equation	Opening, mm [in]	Bar Shape		
		Trap	Rect	Tear
Kirschmer β	6 [0.25]	1.3	1.2	0.76
	13 [0.5]	1.7	2.1	1.4
	19 [0.75]	2.4	2.42	1.2
Bernoulli C	6 [0.25]	2.2	2.5	3.5
	13 [0.5]	2	2.1	2.2
	19 [0.75]	1.4	1.5	2.5

TABLE 2. Revised β and C coefficients for matching Tests

Figures 14 through 22 show the revised headloss charts with the revised coefficients.

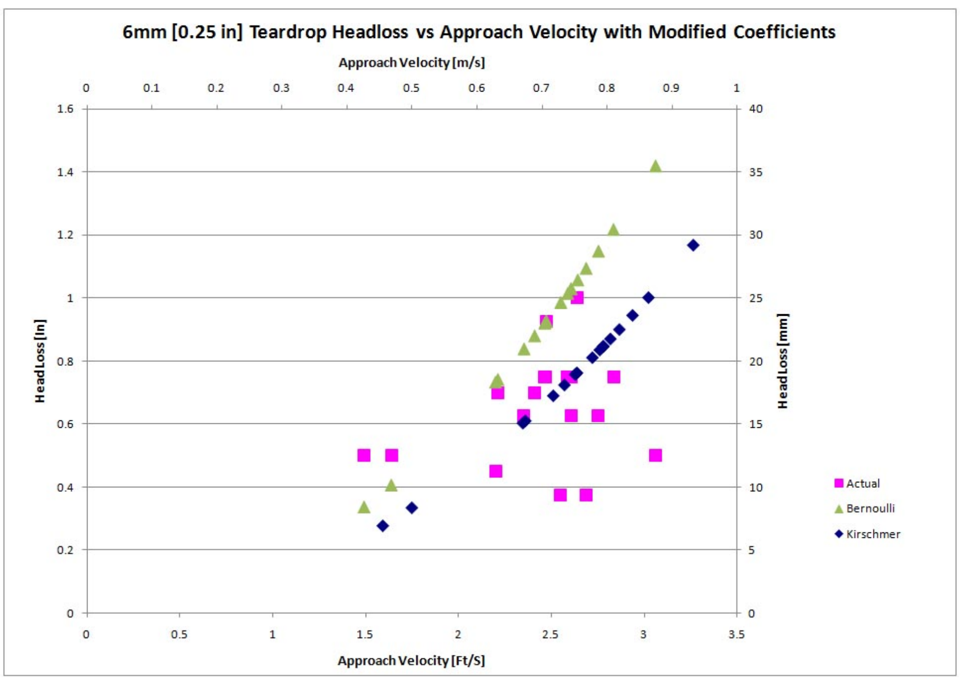
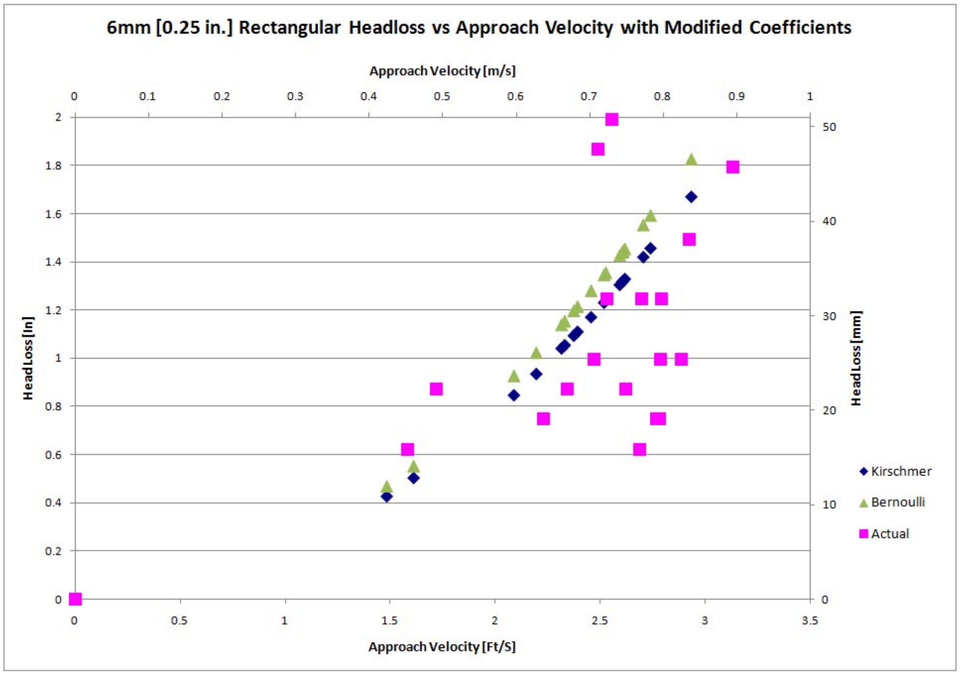


Figure 14.



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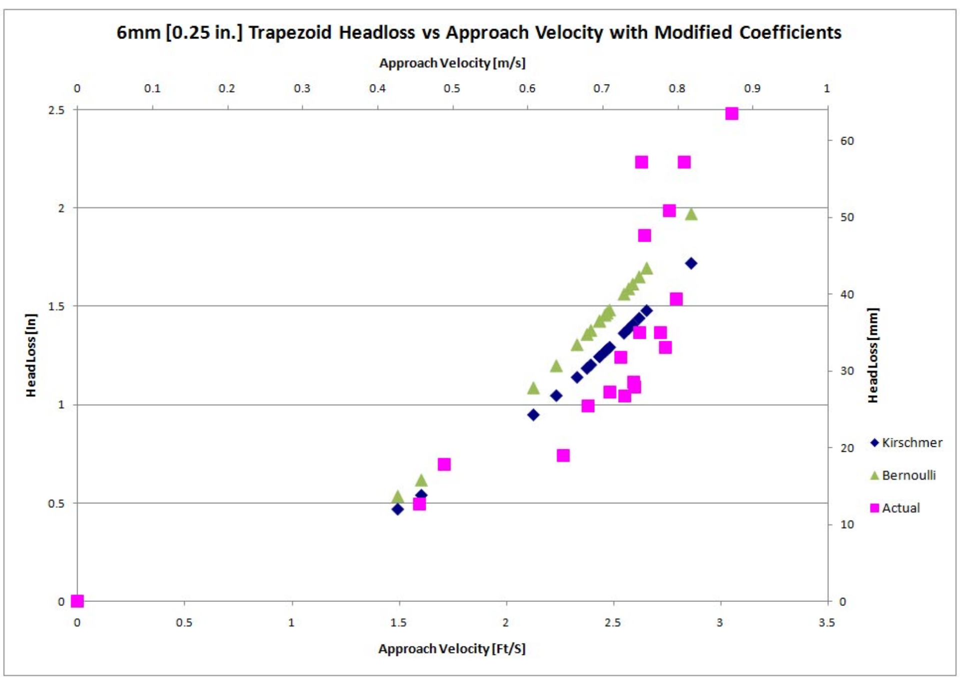
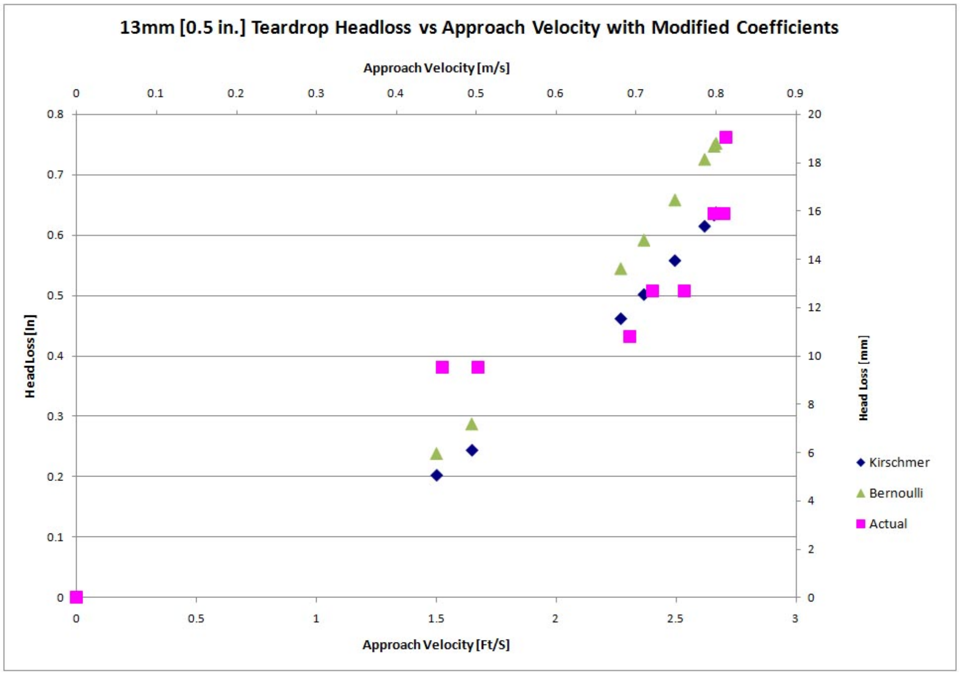


Figure 16.



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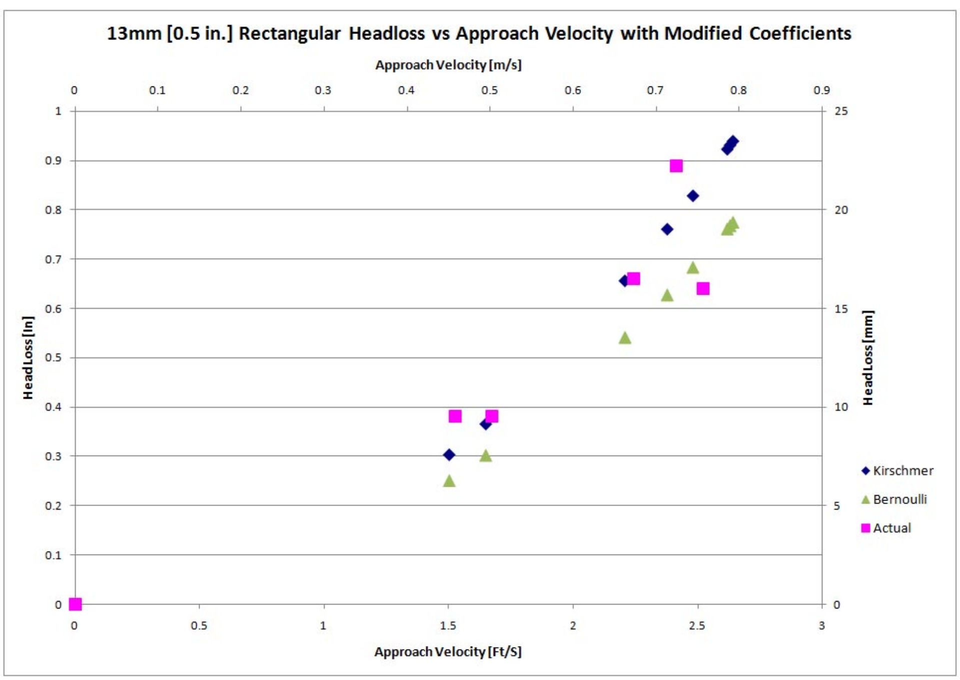

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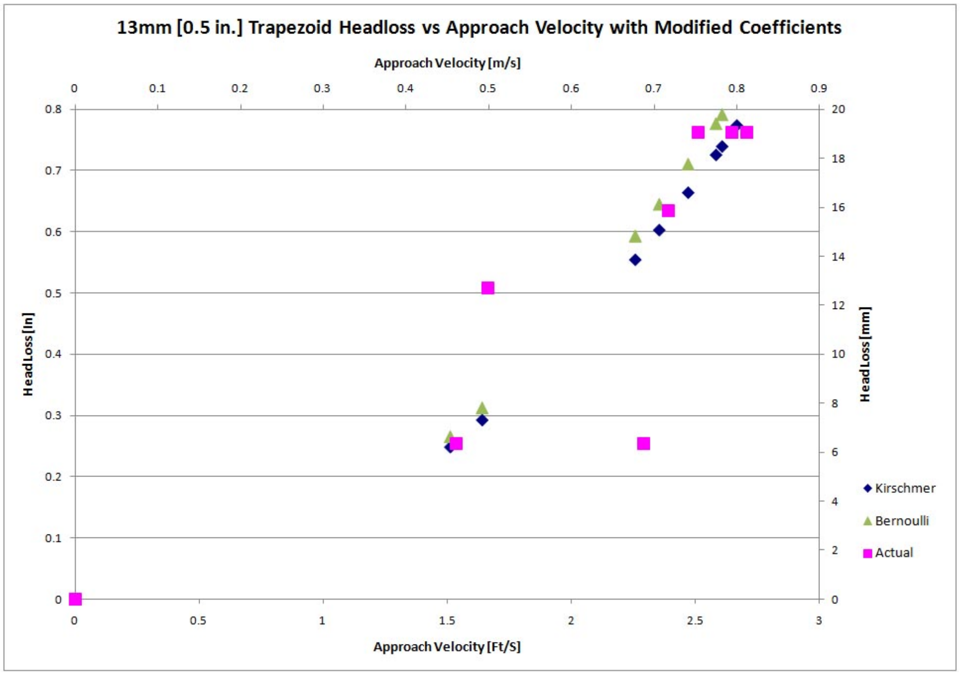

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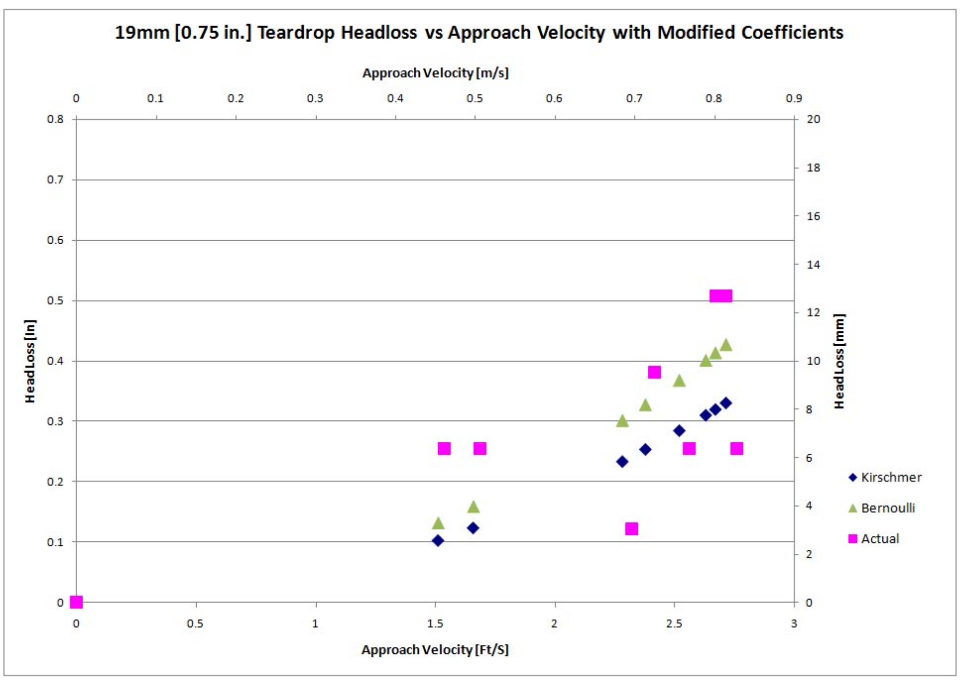

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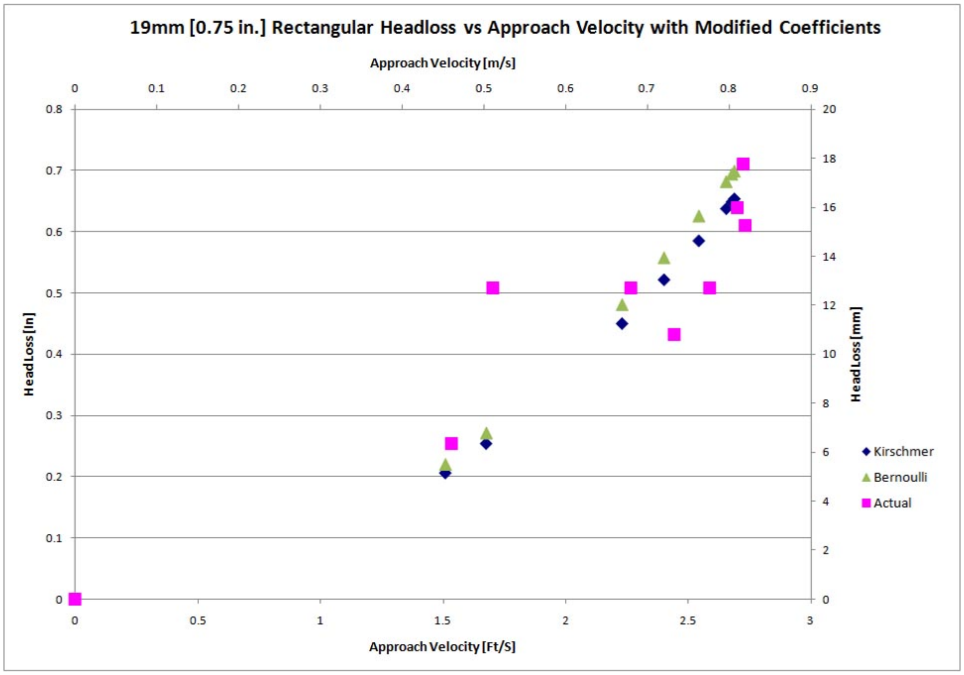

Figure 21.

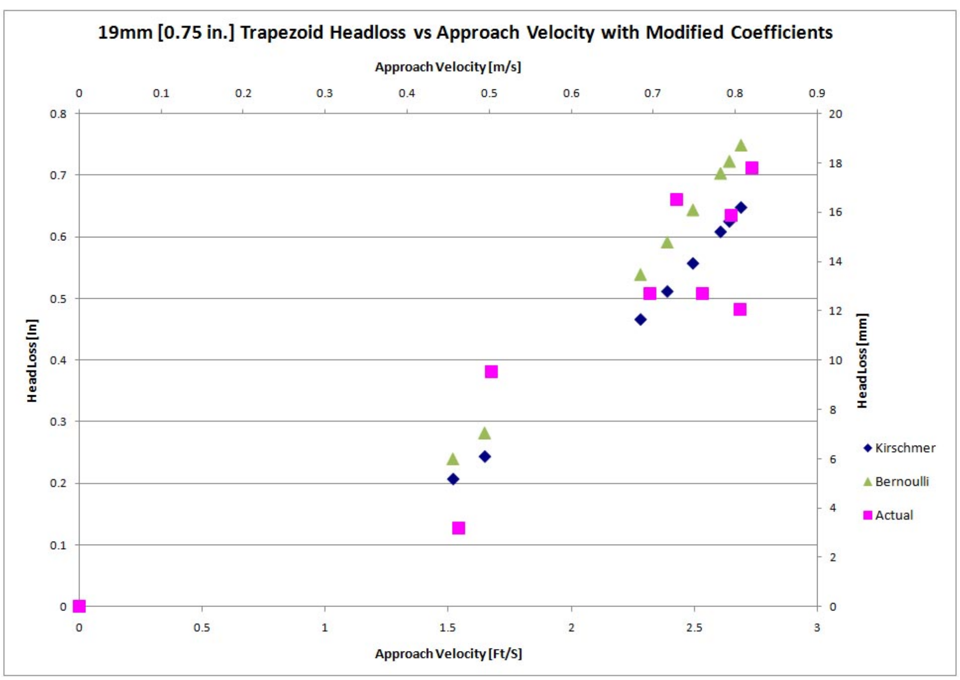

Figure 22.

Figures 14 through 22 seem to indicate that the β and C coefficients in addition to being dependent on bar shape, they are also a function of the opening size. Therefore, a correlation between these coefficients and opening size was developed and is illustrated on Figures 23 and 24.

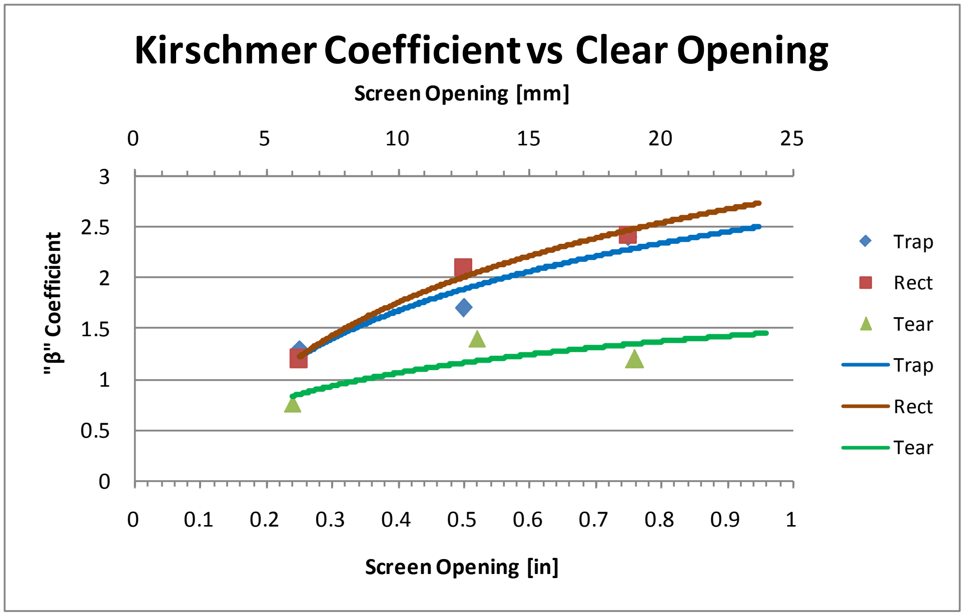

Figure 23.

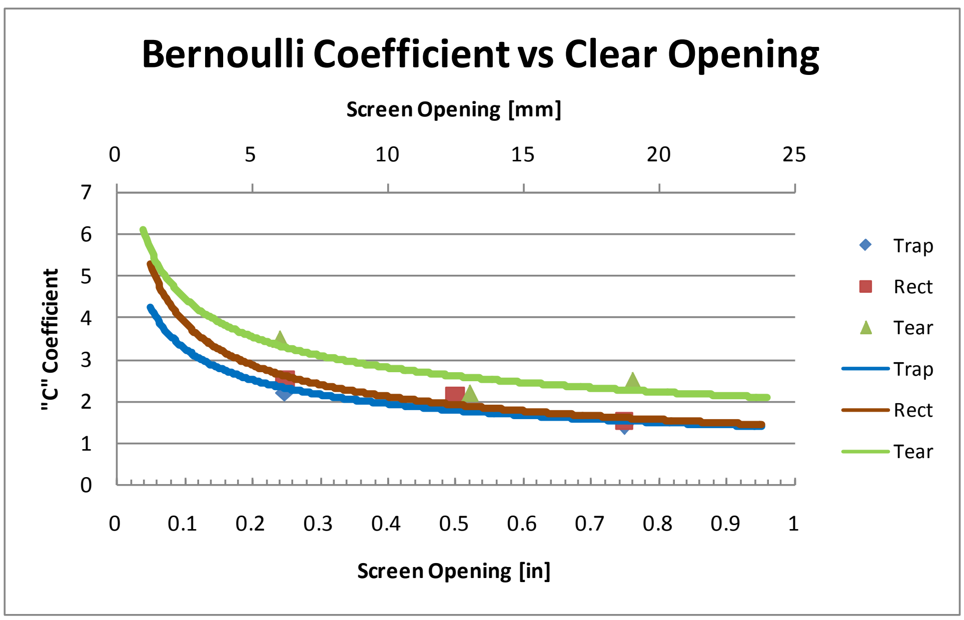

Figure 24.

The following conclusions can be drawn from Figures 23 and 24.

1. The Kirschmer β coefficient seems to be smaller with smaller bar opening, which may be counterintuitive as one would think that at smaller openings the headloss should be greater thus this number should be larger. However, upon analyzing the Kirschmer equation in more detail it was noticed that the bar opening term in the equation (b) starts governing the equation at smaller openings (it is in the denominator and to the power of 1.33). Thus, even though the β coefficient is smaller in magnitude for smaller openings, the headloss across the screen is in fact larger as it was expected.

2. The Bernoulli C coefficient does show wider variability over the bar opening range evaluated.

3. Based on the results from the tests performed it seems that the variability of the β and C coefficients between the rectangular and trapezoidal bars is not very large. Conversely, the teardrop bar does seem to have larger variability with the other two bar shapes evaluated regarding the coefficients β and C.

4. More studies are probably required to help develop and refine the β and C coefficients.

COMPUTATIONAL FLUID DYNAMICS (CDF) ANALYSIS

A CFD model (Fluent) was used to simulate the flow through the 6 mm [0.25 in] screen in the test channel. The CFD model solves the Reynolds-averaged, Navier-Stokes equations describing the flux of mass and momentum within a fixed domain subject to specified boundary conditions. Two different flow conditions were modeled with a specific set of downstream conditions.

Models were solved for pressures at conditions of 85 liters/second [3 CFS] and 142 liters per second [5 CFS]. The channel was configured with a 0.3 m [12 in.] weir at the discharge end.

Figures 25 and 26 show the model setup including the pressure contours of the channel.

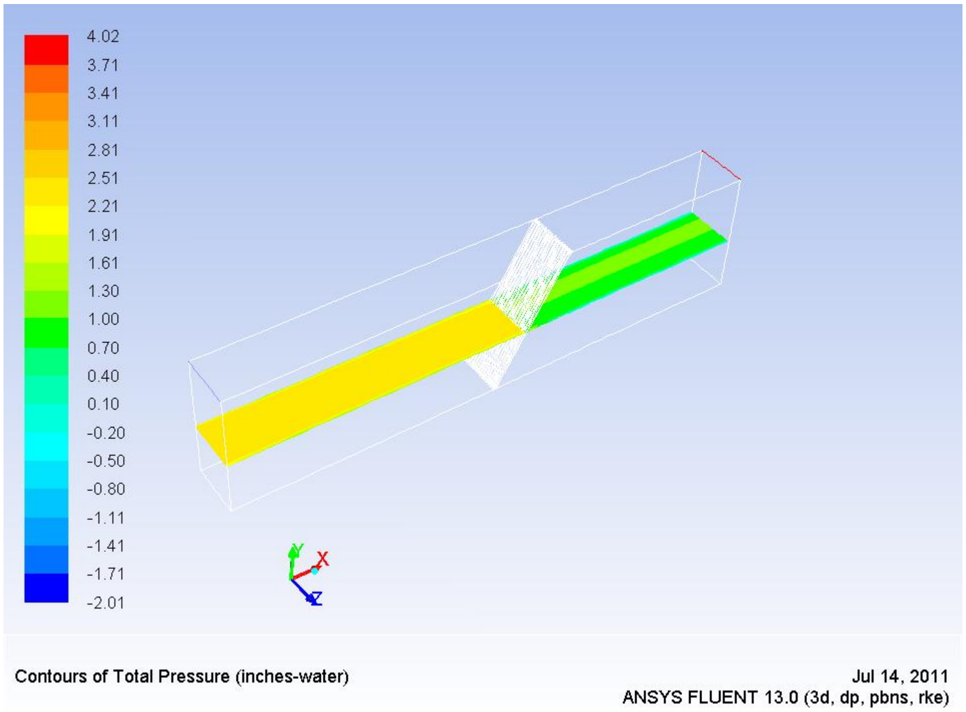

Figure 25. – Overall Model Setup and Total Pressure Contours

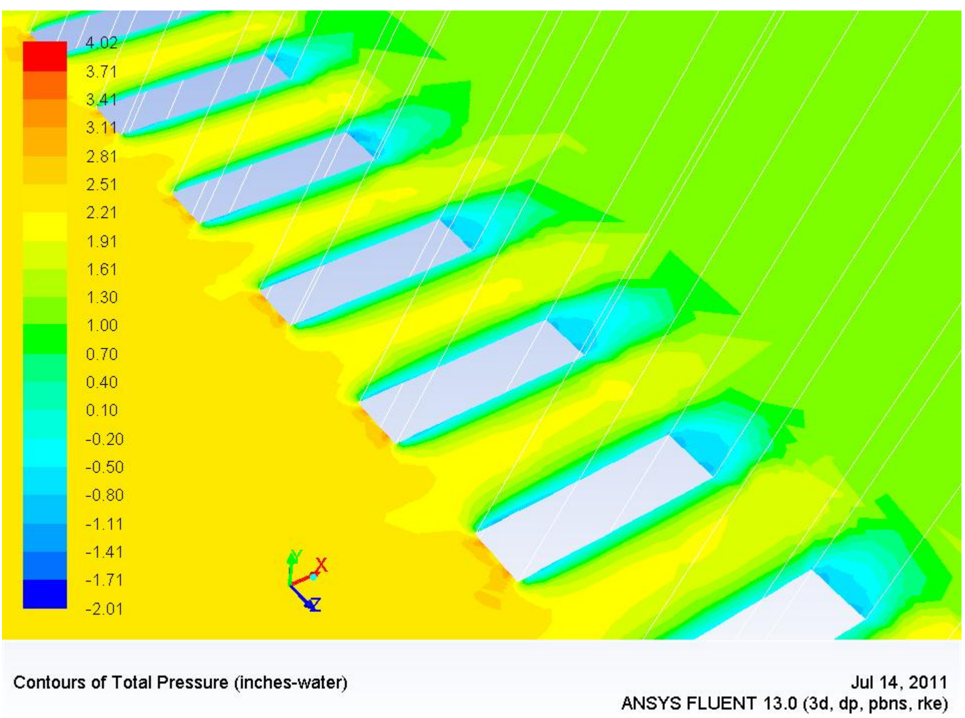

Figure 26. Total Pressure Contours Through Screen (6 mm rectangular bars)

Only two different CFD runs were performed, due to the significant amount of time for setting and running CFD models. The results of the two iterations conducted are shown on figure 27 where they are compared against the channel headloss data and the unmodified Bernoulli and Kirschmer predictions. Even though no conclusions can be drawn from two data points, the CFD model results do show that this method seems to be much more accurate than the original Bernoulli and Kirschmer methods.

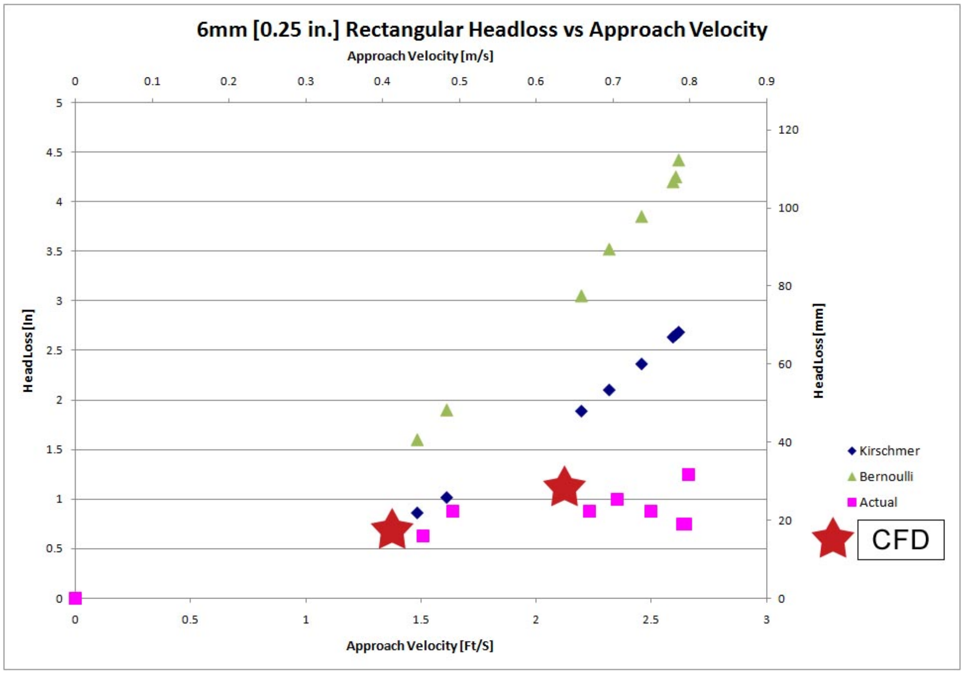

Figure 27. Headloss data including CFD modeling headloss data (6 mm [0.25 in.] rectangular bar screen)

TEST 3 – CONFORMATION TEST

The plot area was formatted as headloss as a function of downstream water depth. This type of graphical representation is frequently used by screen manufacturers to give a representation of all flow conditions a bar screen may encounter. Actual headloss and upstream water depth were plotted as well as theoretical traces for each Bernoulli and Kirschmer data point. The theoretical traces were calculated and plotted using modified coefficients calculated as text book values. Bernoulli traces were calculated using an iterative solver algorithm and solving for upstream velocity based on theoretical downstream level. Upstream level and headloss were calculated once upstream velocity was determined. Only charts for 6mm [0.25 in.] opening with teardrop, trapezoid, and rectangular shapes are shown.

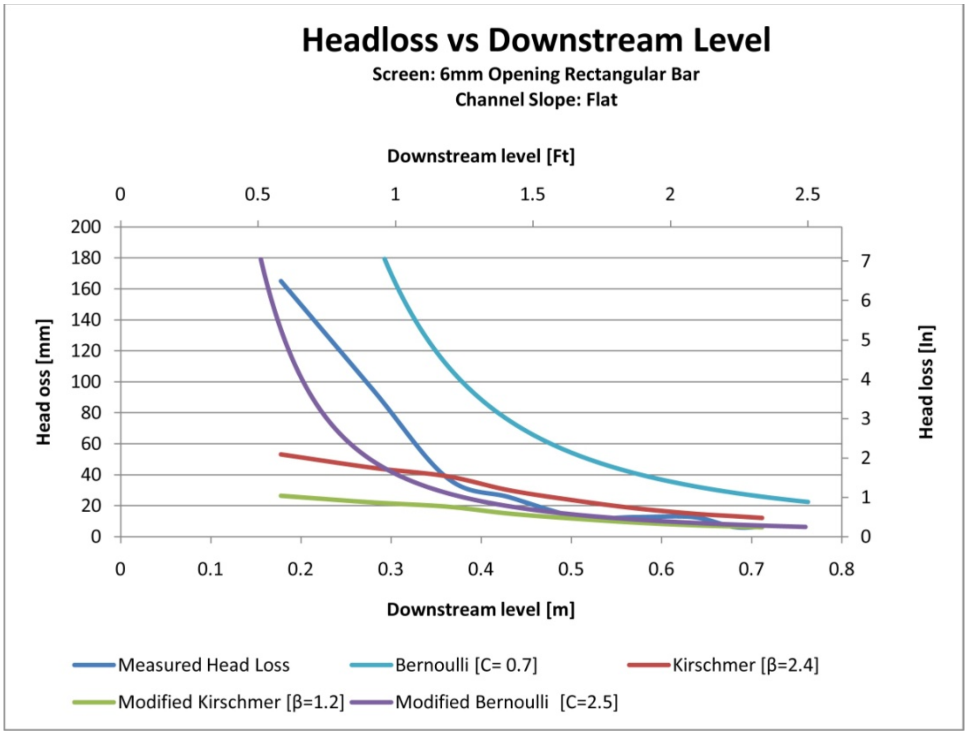

Figure 28.

Figure 29. Photo of transition from sub-critical to super critical.

Figure 30. Photo of transition from sub-critical to super critical.

Figure 31. Photo of transition from sub-critical to super critical.

The following conclusions can be drawn from the Figures 32 and 33.

1) Traces from the modified coefficients correlate within 15 percent of measured actual data while the downstream water depth is sub-critical. Traces from text book coefficients deviate on the order of several times.

2) The theoretical Kirschmer traces that were calculated with modified and text book coefficients appeared to deviate exponentially during and after the downstream water flow conditions became super critical in the channel. It is best to avoid super critical flow in operational conditions. The Kirschmer equation has valid benefits to predicting headloss across a bar screen and should not be neglected.

3) The theoretical Bernoulli traces that were calculated with modified and text book coefficients deviated significantly while the downstream water flow conditions became super critical in the channel. However after flow conditions downstream finished

transitioning from sub-critical flow to super critical flow the modified Bernoulli trace was within 10% of the actual flow trace. This is an interesting point however it cannot be confidently concluded that Bernoulli is accurate when super critical flow exists downstream.

TEST 3 – CAPTURE RATE TESTING

Figures 32 and 33 represent the impact headloss and approach velocity have on a screen's ability to capture fabric debris. Fabric was chosen as it is a very common solid found in municipal waste streams. The fabric was cut into pieces 6mm x 25 mm [.025 in. x 1 in.], selected as a passable solid in one direction.

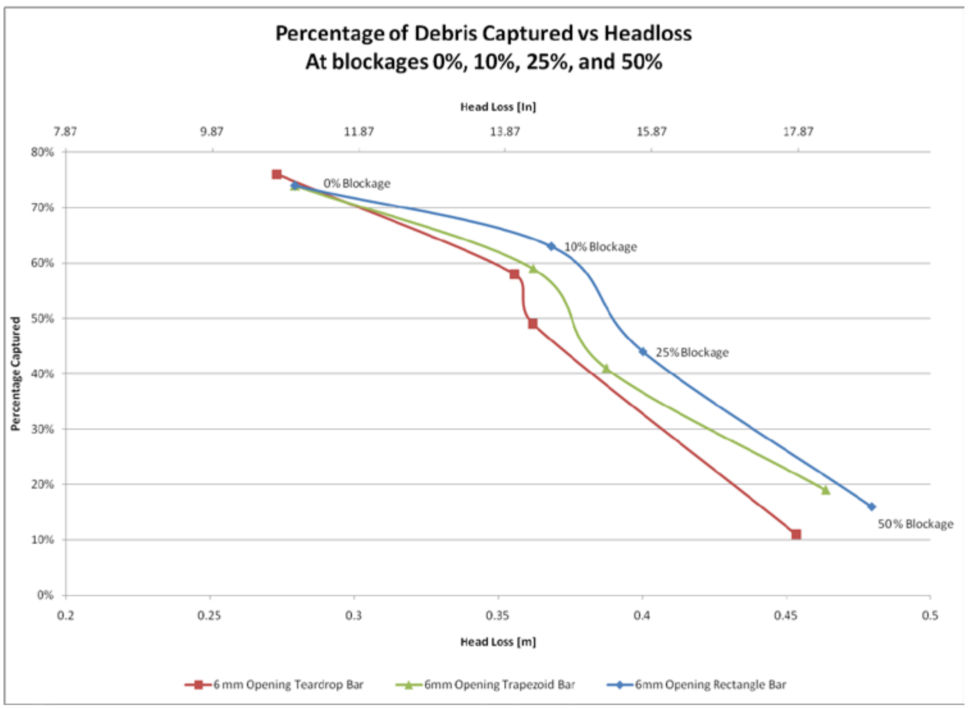

Figure 32.

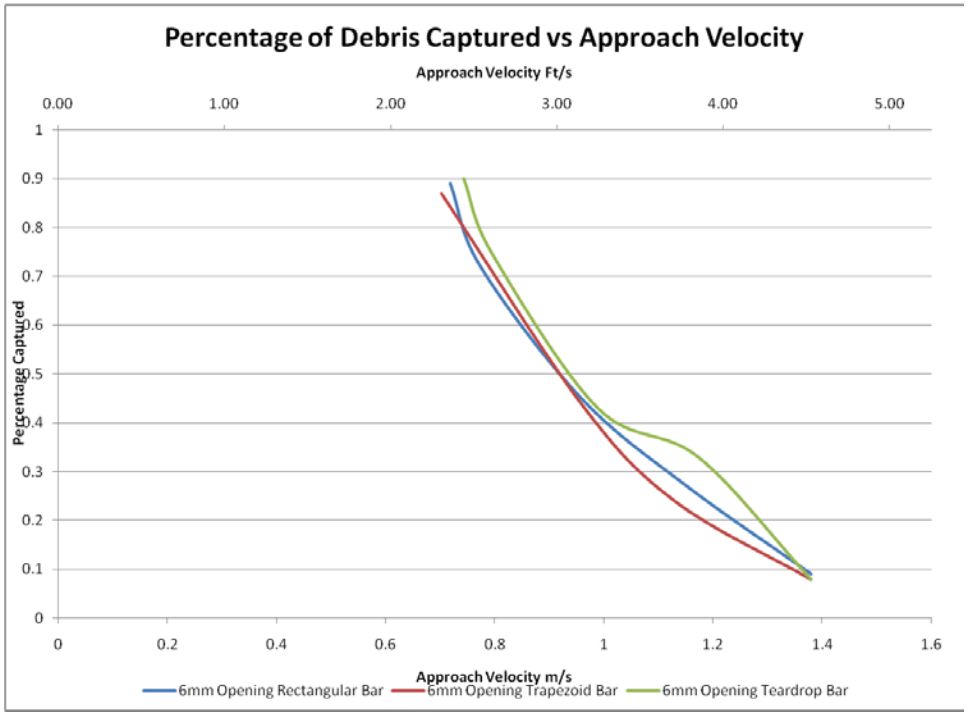

Figure 33.

Figure 34. Photo of solids used for capture testing.

It is beyond the scope of this paper to completely evaluate the relationship between flow conditions and capture.   However several interesting points are worth notation:

1) Both headloss and velocity appear to have significant impact on capture through a bar screen.
2) It appears that percentage of solids captured degrades rapidly as the bar screen is subjected to excessive approach velocity.
3) Bar screens are especially susceptible to headloss caused from blockage. In figure 32 as blockage is added, headloss increases, and capture rate decreases. Care should be exercised to control conditions where a screen is left to build headloss.
4) It is interesting that all three bar types appear to have very similar capture capabilities while being subject to the same flow conditions.

CONCLUSIONS

Current modeling of headloss in a municipal waste stream is not accurate using currently available equation coefficients. Revised coefficients need to be used to accurately model headloss. More testing is necessary to refine and validate these initial findings. CFD modeling seems to have potential to be a good tool for estimating headlosses in bar screens even though it does require considerable time for setting and running the models. A bar screen's ability to capture debris is quite dependant on approach velocities, headloss and blockage. It is important to select the appropriate equipment to properly maintain these parameters in order to have more consistent site hydraulics and to promote process reliability and sustainability, long term . Flow in the channel downstream of the bar screen should be maintained in the sub-critical condition, as supercritical flow conditions (even though rarely seen in wastewater treatment screening systems) have negative effects on screening due to the increased slot velocities and associated headloss. Operational strategy of a bar screen is important to ensure screens are maintained as clean as possible at all times. Systems that build headloss in order to initiate a cleaning cycle should be configured to use the minimum amount of head that provides adequate debris capture. As worldwide water resources grow increasingly precious, the need for consistent and predictable plant hydraulics expands as well. The modified equations presented here are intended to support the continued evolution of the screening industry and to make a contribution to the continuing efforts toward the improvement of plant operating economies and efficiencies.

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