Intake Flow Measurement at Lower Granite Power Plant by Acoustic Scintillation: Results and Comparison with Winter-Kennedy and Model Test Data

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Abstract

As part of the ASME PTC-18 Committee's Short Converging Intake Project to evaluate methods for measuring discharge in short converging intakes, acoustic scintillation measurements were made in December 2004 at the US Army Corps of Engineers' Lower Granite Power Plant on the Snake River. Acoustic time-of-travel measurements in the intake and Winter-Kennedy differential pressure measurements were made at the same time, and model test results were also available. There is no code-accepted absolute flow measurement method for short-intake plants like Lower Granite to be used as a reference, but the simultaneous operation allowed comparisons among the three methods to be made on a relative basis.

The Lower Granite plant is equipped with fish diversion screens, which are designed to divert part of the flow in the upper portion of the intake into a bypass channel so that juvenile salmon migrating downstream do not pass through the turbine. When in place, the screens produce a highly distorted flow field in the intake. The program at Lower Granite therefore afforded an opportunity to compare the performance of intake flow measurement instruments under two different sets of hydraulic conditions: one relatively good and the other poor. The ASFM flows presented here have been reprocessed to incorporate recent refinements to the acoustic scintillation data processing algorithms, developed since 2008 and used in the 2009 Kootenay Canal absolute flow comparison tests. This paper compares the relationship between the acoustic scintillation flows and Winter-Kennedy measurements made at Lower Granite Dam with and without screens in place to the corresponding relationship observed in the model. Good agreement in the relationship was found between the model and observed cases.

Introduction

In December 2004, the Walla Walla District of the U. S. Army Corps of Engineers (USACE) contracted for a comparative flow measurements at Lower Granite Dam on the Snake River as part of a turbine performance measurement program under the Corps' Power Plant Efficiency Program. Several different methods for measuring flow in the intake were to be tested in conjunction with the American Society of Mechanical Engineers (ASME) PTC-18 Committee's Short Converging Intake Project. The goal of the project is to evaluate methods for measuring flow in the short, converging intakes typical of low-head hydropower plants and to assess their suitability for eventual inclusion in the performance test code. Of the methods under consideration (current meters, acoustic travel time and acoustic scintillation), only acoustic travel time and acoustic scintillation were used in the Lower Granite program. Relative flow data, in the form of Winter-Kennedy differential pressure measurements were also collected.

Lower Granite Dam is typical of the large, low-head plants on the Columbia and Snake River system, with a head of approximately 100 feet, and multiple turbines of approximately 150 MW capacity. Each turbine is fed by a three-bay intake, 21.2 feet wide by 47.2 feet high. The measurements were made in Unit 4, with no screens in place and with Extended Submerged Bar Screens (ESBS) in place. Data were collected over the operation range of the existing cam curve, and also at a series of off-cam conditions to develop a revised curve. Here, we will analyze the relationship of ASFM discharges to the Winter-Kennedy data under both sets of conditions. Data were also available from a series of model tests of the Lower Granite unit, with and without fish diversion screens installed, that were performed by VA TECH VOEST MCE of Linz, Austria under contract to USACE. Those model tests included both flow and pressure differential, so a comparison of the relationship between them in the model to that observed in Lower Granite Unit 4 could be made.

Flow Measurement by Acoustic Scintillation Drift

The Acoustic Scintillation Flow Meter (ASFM) uses a technique called acoustic scintillation drift [1, 2] to measure the flow velocity perpendicular to a number of acoustic paths established across the intake to the turbine. Short (16 μsec) pulses of high-frequency sound (307 kHz) are sent from transmitting arrays on one side to receiving arrays on the other, at a rate of approximately 250 pings /second. Fluctuations in the amplitude of those acoustic pulses result from turbulence carried along by the flow. The ASFM measures those fluctuations (known as scintillations) and from them computes the lateral average (i.e. along the acoustic path) of the velocity perpendicular to each path.

Typically, the ASFM sensors are installed on frames which are placed in the stoplog slots of each bay; the frames are designed so that the transducer faces sit flush with the sidewalls of the intake (Fig. 1). At Lower Granite Dam, a double acoustic scintillation system was used, with 20 paths in each bay, to provide greater resolution of the velocity profile, particularly for the distorted velocity profiles produced when the ESBS were present.

In the time since the measurements were made in 2004, improvements have been made in two parts of the data processing algorithm: the filtering applied to the time series, and the method by which the results from the individual blocks within the time series are combined to compute the flow velocity, as described in [3]. The data collected at Lower Granite has been reprocessed with these improvements, and the reprocessed data are used in the analysis that follows.

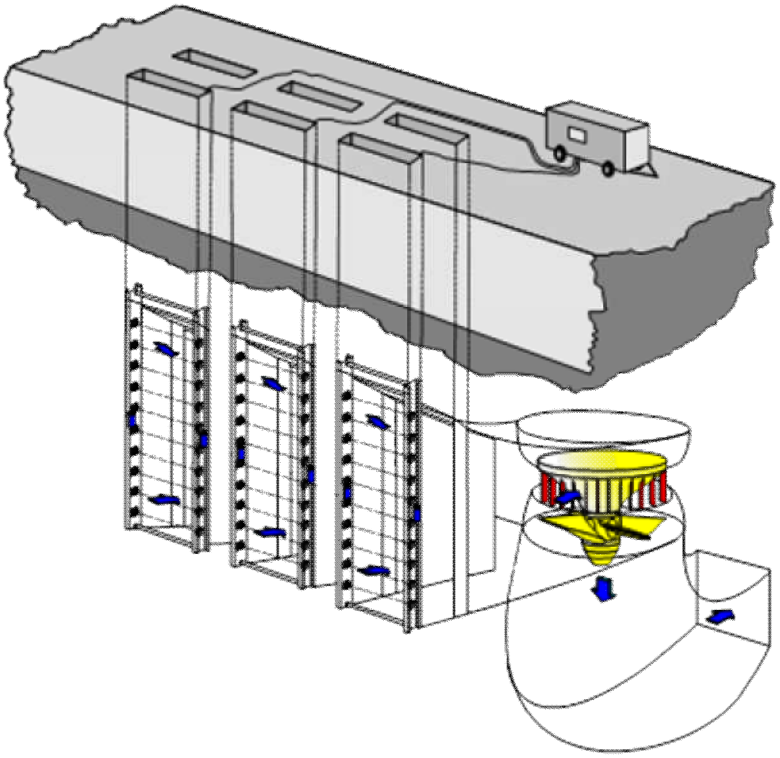

Figure 1: Typical ASFM installation in a 3-bay intake

Changes with respect to the original 2004 results are small for the screens-out cases, being on average a 0.4% increase, showing no trend with discharge in the fractional difference. With screens in however, the difference is greater, ranging from 0.9% at the minimum discharge to 3.0% at the maximum discharge and averaging 2.0%.

Measurement Program

With no screens in place, seven conditions were measured - one on-cam and six off-cam. Eight conditions were measured with the ESBS fish screens in place - one on-cam and seven off-cam.

Table 1 summarizes the data collection sequences. In each case, four replicate runs at 30 seconds per level were completed in about 30 minutes during which time Hydroelectric Design Center (HDC) personnel completed five sets of Winter-Kennedy measurements. The individual ASFM measurements are useful as they yield information on the steadiness of the flow rate and the repeatability of the ASFM. A flow rate is computed from each of the four runs and then averaged.

In several cases, repeat measurements were taken at the same servo setting in order to verify the discharge values.

Table 1: Schedule of data collection

Unit	Data Set	ESBS Screens	Start Date (YYYY/MM/DD)	Start Time (hh:mm PST)	End Date (YYYY/MM/DD)	End Time (hh:mm PST)	# of Individual Conditions	# of Repeats
4	On Cam	OUT	2004/12/16	09:27	2004/12/16	15:29	10	1
	Off Cam - 19.75 BA	OUT	2004/12/17	07:15	2004/12/18	17:19	4	12
	Off Cam - 22.5 BA	OUT	2004/12/17	09:50	2004/12/17	12:03	4	0
	Off Cam - 24.0 BA	OUT	2004/12/17	12:24	2004/12/17	14:36	4	0
	Off Cam - 26.16 BA	OUT	2004/12/17	14:57	2004/12/17	17:09	4	0
	Off Cam - 28.25 BA	OUT	2004/12/17	17:27	2004/12/18	17:53	4	2
	Off Cam - 30.0 BA	OUT	2004/12/18	07:49	2004/12/18	10:08	4	0
	On Cam	IN	2004/12/10	10:33	2004/12/10	17:12	11	0
	Off Cam - 19.75 BA	IN	2004/12/11	08:00	2004/12/13	18:02	5	7
	Off Cam - 22.0 BA	IN	2004/12/11	11:16	2004/12/11	14:22	5	0
	Off Cam - 24.0 BA	IN	2004/12/11	14:42	2004/12/11	17:42	5	0
	Off Cam - 26.0 BA	IN	2004/12/12	08:07	2004/12/12	11:44	6	0
	Off Cam - 28.0 BA	IN	2004/12/12	12:08	2004/12/13	17:25	5	2
	Off Cam - 30.0 BA	IN	2004/12/12	15:18	2004/12/12	17:29	4	0
	Off Cam - 32.0 BA	IN	2004/12/13	09:00	2004/12/13	11:58	5	0

BA = blade angle
ESBS = Extended Submerged Bar Screens

Analysis and Comparison of Flow Data

Lower Granite 2004 Measurements

An assessment of the quality of the ASFM data can be made by evaluating the degree to which the fit between the ASFM flows and the Winter–Kennedy pressure differential follows the theoretical equation. The standard form for the relationship between flow and the pressure tap difference is given by an equation of the form

$$Q = kd^{n} \tag{1}$$

The values for the exponent n are restricted to 0.5 ±0.02, applicable over one half the maximum flow rate. Here, following [4], the W-K data is fitted to an equation of the form

$$Q = kd^{1/2} + c \tag{2}$$

This form is preferred to the standard power law fit as the latter can introduce spurious non-linearity during inter-comparison of data sets [4, 5]. It is also more suitable for the estimation of confidence intervals. The intercept *c* is interpreted as a measure of the stability of the flow distribution as the flow approaches zero. It has been found to be statistically significant only in cases where non-uniform flow conditions such as separation are known to exist in the intake. For the high Reynolds numbers at normal operating conditions, such regions are relatively stable, and have a small, but fixed effect on the flow distribution at the Winter-Kennedy piezometer taps. Such features change their form at low flow speeds, and hence the flow distribution changes slightly throughout the system.

Wittinger [6] presents the results of the comparative flow measurements for the original 2004 processing of the ASFM data. At the time of the tests, both the contractors and the HDC test team concluded that a region of separated flow existed at the roof in the region of the gate slots, close to the measurement plane of the ASFM system.

Equation (2) was used to analyze the relation between the reprocessed ASFM flows and the Winter-Kennedy pressure differences. The Winter-Kennedy plots are presented separately for the on-cam and for the individual off-cam runs, as it was found that the off-cam Winter-Kennedy plots differed significantly from the on-cam plots. Figure 2 for runs without the screens fitted shows the off-cam plots superimposed on the on-cam plot, and it can be seen that although the individual off-cam plots are linear, in general they are not aligned with the on-cam data.

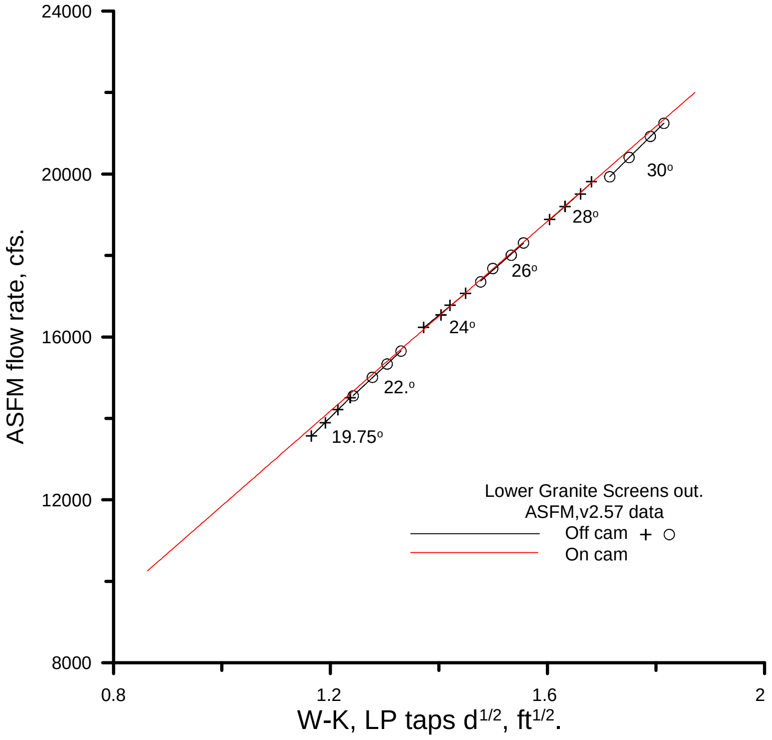

Figure 2. Winter-Kennedy plots for on-cam and off-cam runs without fish screens.

The difference can clearly be seen in the case of the 19.75° and 30° blade angle runs. The intercept *c* is not statistically significant for the on-cam data, but for the off-can runs it is significant for all but the 24° and 26° blade angles where the fit is closely aligned with the on-cam fit. Table 2 lists the slopes and intercepts of the Winter-Kennedy fits for all these cases. The final column lists the ratio of the difference in slopes between each off-cam run and the on-cam data to the 95% confidence interval of the off-cam slopes, a measure of the statistical significance of the mismatch between the on-cam and off-cam slopes. (Ratios >1indicate a significant difference in slope.) The high proportion of significant differences suggests that they are a reflection of changes in flow conditions.

Table 2. Winter-Kennedy fits without the fish diversion screens fitted.

Screens out	ASFM Re-processed data		Ratio of on-cam, off-cam slope differences to
Blade angle.	Slope, cfs/ft$^{1/2}$	Intercept, cfs	95% off-cam confidence interval
On cam	11652	206	n/a
19.75	13035	-1612	1.17
22	12429	-877	2.27
24	10958	1193	-0.46
26	11730	50	0.14
28	12085	-509	4.81
30	13173	-2656	73.96

Table 3 lists the corresponding Winter–Kennedy fits with the fish diversion screens in place. The general scatter in all the data is greater, and the intercepts of the fits are only statistically significant for the three off-cam sets for 24^{o}, 30^{o} and 31.5^{o} blade angles. Note that in only one case, the 30^{o} blade angle, is the difference in slope statistically significant.

Table 3. Winter-Kennedy fits with the fish diversion screens fitted.

Screens in	ASFM Re-processed data		Ratio of on-cam, off-cam slope differences to
Blade angle	Slope, cfs/ft$^{1/2}$	Intercept, cfs	95% off-cam confidence interval
On cam	12664	-146	n/a
19.75	14122	-1817	0.63
22	12423	173	-0.25
24	13543	-1259	1.30
26	12519	27	-0.42
28	12424	4	-0.78
30	10512	3289	-6.15
31.5	13958	-3065	1.01

The systematic nature of the differences between the on-cam and off-cam Winter-Kennedy fits for the screens-out condition is further illustrated in Figure 3, which, with the exception of the 30^{o} blade angle point, shows a tight linear relationship between the slope *k* and the intercept *c*. The decrease in the intercept as the slope increases is a natural consequence as the fits are constrained to tend towards the on-cam line. The precise linear relationship is surprising however, and with the exception of the 30^{o} point, extensions of the off-cam fits pass through a single point on the on-cam Winter-Kennedy plot.

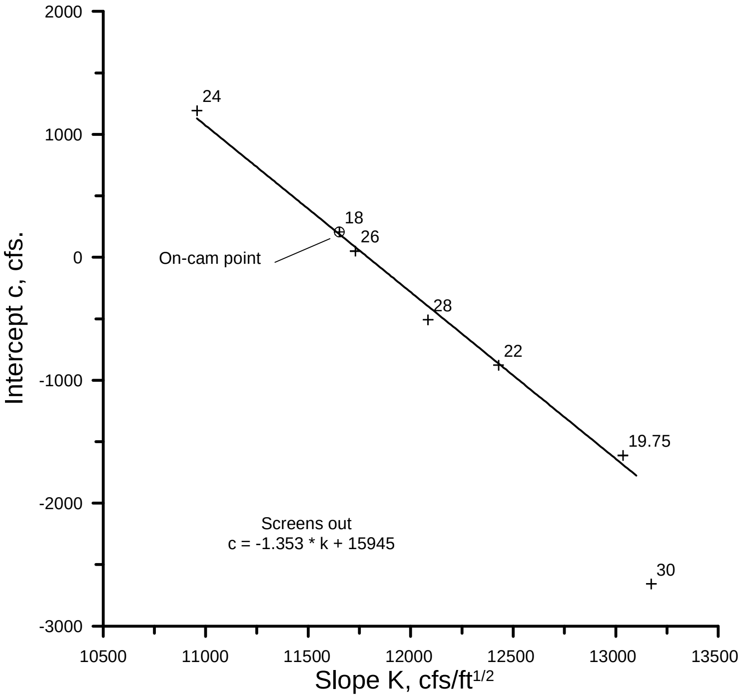

Figure 3. The relation between the slope and intercept for the off-cam W-K fits without fish screens.

The physical cause of the systematic differences between the off-cam and on-cam fits is not clear, although changes in the extent of the region of separated flow is one possibility. Figure 4 for example, shows the off-cam slopes plotted against the gross head, which was the only variable available which provided a coherent picture of changes, however it is not intended to imply a direct cause and effect. The horizontal bars indicate the total range of head values associated with each point.

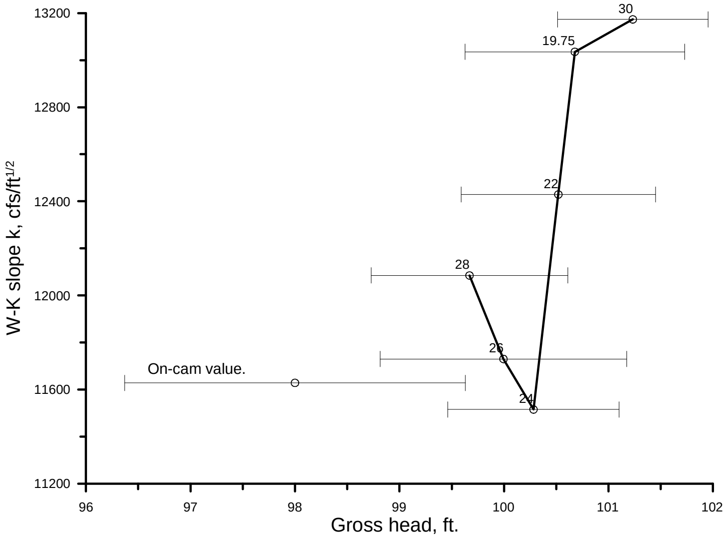

Figure 4. The variation of the off-cam W-K slopes with gross head, screens out.

Comparison with model tests.

A 1:25 scale model of Unit 4 was constructed by VA TECH VOEST MCE in and used to conduct a series of performance tests, with and without fish screens in place [7]. The limited amount of Winter-Kennedy data available from the model tests performed by is shown in Figure 5 below, with the relevant Winter-Kennedy fitting coefficients listed in Table 4, using the directly measured model units. The model Winter-Kennedy data available is confined to the high and low ends of the flow range.

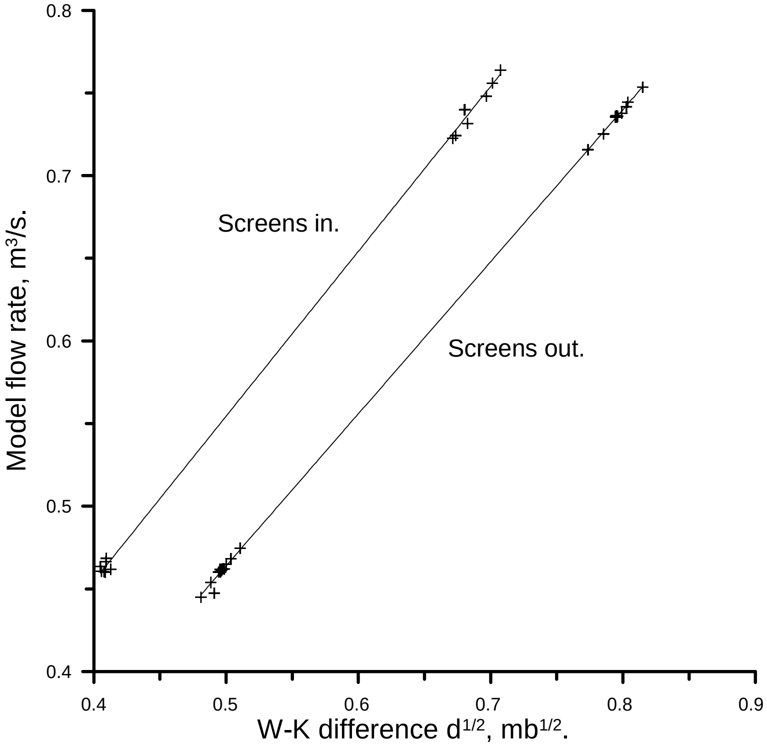

Figure 5. Model test Winter- Kennedy fits with and without fish diversion screens.

Table 4. Model Winter-Kennedy fits, screens in and screens out

Model			
Condition	Slope, $m^3/s/mb^{1/2}$	Intercept, m^3/s	Stdev/Qm
Screens Out	0.920	0.0040	0.0031
Screens In	0.998	0.0557	0.0063

The corresponding on-cam Winter-Kennedy fits for the ASFM data are shown in figure 6, with the details of the fits listed in Table 5. The off cam fits listed are for all off-cam runs taken as a group.

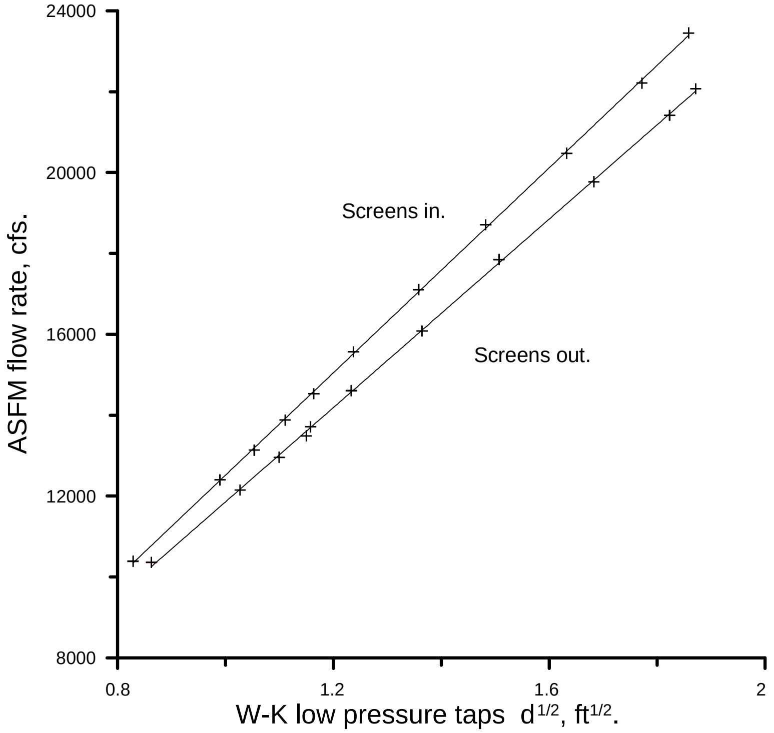

Figure 6. The ASFM Winter-Kennedy fits for on-cam runs with and without fish diversion screens.

Table 5. ASFM Winter-Kennedy fits, screens in and screens out

ASFM			
Condition	Slope, cfs/ft$^{1/2}$	Intercept, cfs	Stdev/Qm
On-cam, Screens out	11652	206	0.00412
Off-cam, Screens out	11681	88	0.00463
On-cam, Screens in	12664	-146	0.00359
Off-cam, Screens in	12301	319	0.00601

The ratio of the standard deviation of the points from the fitted line to the median flow is the same in the model data and the data from the Lower Granite plant. A direct comparison of the model and measured flows, or of the respective fits to the Winter-Kennedy pressure differences, would require accounting for scaling and efficiency step-up factors. Another comparison can be made which does not require those adjustments, by using the ratios of the slopes of their respective screens-in and screens-out fits to the Winter-Kennedy pressure differences, shown in Table 6.

Table 6. Ratios of Winter-Kennedy slopes, screens in/screens out.

Slopes ratio, screens in/screens out	
ASFM on-cam	1.087
ASFM off-cam	1.053
Model	1.084

Of the two alternative fits to the ASFM data, for the on-cam fits the match is almost perfect, with the overall off-cam fits underestimating by 3%. This is not unexpected, given the differences in the individual off-cam fits of the full scale plant. The normalized standard deviations of the fits for the model and the ASFM fits listed in tables 4 and 5 are of similar magnitude. Both the acoustic scintillation and model flows show the same change in relation to the pressure differences when the diversion screens are installed.

Discussion

The improved processing algorithm for the ASFM, used for the Kootenay Canal comparative intake flow tests [8], was used to reprocess acoustic scintillation flow data collected in the 2004 comparative flow tests at Lower Granite Dam. The results were used to compare the relationship between the measured flow and the Winter-Kennedy pressure differences observed for on-cam and off-cam operation, with and without fish screens in place. A modified form of the Winter-Kennedy relation, more suitable for comparisons among multiple flow data sets was used. The reprocessed acoustic scintillation on-cam flows produced a fit against the Winter-Kennedy data with a lower residual sum of squares, 22% less with screens out, and 2.5% less with screens in. The reduction in the residuals without the screens is largely due to the improved averaging technique in dealing with the flow separation. The introduction of the fish screens removes the separated flow region and the averaging technique is less critical. The overall mean reduction of the residuals for the off-cam runs is larger, 17% with the fish screens fitted and 34% without.

There were statistically significant differences between the Winter-Kennedy fits for the on-cam and off-cam results. These were found to be systematic and appear to reflect real changes in the flow conditions, although a specific cause could not be identified, they are probably associated with the separated flow. It would be of interest to examine the simultaneous acoustic time-of-travel measurements for similar behaviour.

The ASFM results were also compared with the VA TECH VOEST MCE model tests. The fits between the flow and pressure differential were of equal quality in each case. The change in the slope of the fit of the on-cam acoustic scintillation flows to the Winter-Kennedy data with ESBS installed was within 0.3% of the ratio of the model tests, showing that the changes in the relation between acoustic scintillation flows and the pressure difference data resulting from the installation of the ESBS were consistent with those observed in the model. The slope ratio for the combined off-cam ASFM fits is 3% low; given the systematic variations in the individual fits, the on-cam data is believed to be more compatible with the model.

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