UNCERTAINTY IN THE CALIBRATION OF THE DH-59 SUSPENDED SEDIMENT SAMPLER

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MANAGEMENT PERSPECTIVE

Suspended sediment concentrations are an important indicator of water quality in rivers. To ensure that reliable data are obtained, the Monitoring and Surveys Division (MSD) of the Surveys and Information Systems Branch (SISB) of Environment Canada, is in the process of developing a quality assurance program for the 500 samplers of various types currently in use by the Department. The National Water Research Institute (NWRI) is assisting SISB in the development of a calibration strategy for suspended sediment samplers used in the national program.

In this report the calibration of the DH-59 suspended sediment sampler is examined. It was found that individual samplers can be calibrated with a high degree of repeatability, but that there is a large variability from sampler to sampler at lower velocities, partly as a function of the operating mode of the sampler, either nozzle control or vent control.

PERSPECTIVES DE LA DIRECTION

La concentration de sédiments en suspension est un indice important de la qualité de l'eau dans les cours d'eau. La Division du contrôle et des relevés (DCR) de la Direction des relevés et systèmes d'information (DRSI) d'Environnement Canada est en train de mettre sur pied un programme d'assurance de la qualité pour vérifier la fiabilité des données fournies par les 500 échantillonneurs appartenant à divers types utilisés actuellement au ministère. L'Institut national de recherche sur les eaux (INRE) collabore avec la DRSI pour élaborer une stratégie d'étalonnage des échantillonneurs de sédiments en suspension utilisés dans le cadre du programme national.

Dans le présent rapport, on s'est penché sur l'étalonnage de l'échantillonneur de sédiments en suspension DH-59. On a observé que chaque échantillonneur peut être étalonné avec un taux élevé de répétabilité, mais qu'il existe une grande variabilité d'un échantillonneur à l'autre à de faibles vitesses, en partie à cause du mode de fonctionnement de l'échantillonneur, à gicleur ou à évent.

ABSTRACT

Tests were conducted in the towing tank at NWRI on the DH-59 sediment sampler with carefully selected nozzles. Statistical analysis of the test data were conducted. It has been shown that individual samplers can be calibrated with a high degree of repeatability but that the variability of calibrations from sampler to sampler was quite high at the lower velocities. It was further shown that the performance of the sampler was sensitive to changes in the velocity coefficient of the 3.2 mm nozzle. Similar variabilities in the velocity coefficient for the 4.8 mm and 6.4 mm nozzles did not affect the performance of the sampler. Similar tests on other types of samplers are proceeding.

RÉSUMÉ

Des essais ont été effectués sur l'échantillonneur de sédiments DH-59 à l'aide de gicleurs soigneusement choisis dans le bassin à chariot mobile de l'INRE. Une analyse statistique des données a été effectuée. On a observé que chaque échantillonneur pouvait être étalonné avec un taux élevé de répétabilité, mais que la variabilité de l'étalonnage était assez élevé d'un échantillonneur à l'autre aux vitesses les plus faibles. On a en outre montré que le rendement de l'échantillonneur était sensible au changement du coefficient de vitesse du gicleur de 3,2 mm. Une variation semblable du coefficient de vitesse des gicleurs de 4,8 mm et de 6,4 mm n'avait pas d'effet sur le rendement de l'échantillonneur. Des essais semblables sur d'autres types d'échantillonneurs sont en cours.

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1. INTRODUCTION

Data of suspended sediment concentration in rivers have become increasingly important because the fine fractions of the sediment load are known to be carriers of toxic substances. As a result, suspended sediment concentrations are an important indicator of water quality in rivers. The accuracy of all suspended sediment samplers must be checked to ensure that reliable data are obtained throughout the data collection program conducted by the federal Department of the Environment. At the present time, the Monitoring and Surveys Division (MSD) of the Surveys and Information Systems Branch (SISB), with the assistance of the National Water Research Institute (NWRI), is in the process of developing a calibration strategy for all suspended sediment samplers used in the national data gathering program. This report presents the results of tests conducted on the DH-59 sampler in the towing tank of the NWRI Hydraulics Laboratory at Burlington, Ontario.

2. PRELIMINARY CONSIDERATIONS

The purpose of the suspended sediment sampler is to obtain a sample that is representative of the water-sediment mixture moving in the vicinity of the sampler. During the sampling, a volume of the water-sediment mixture is collected in the sampler over a measured interval of time, using predetermined transit rates (Guy and Norman 1970, Beverage 1979). From the measured volume and the transit time, the flow rate into the sampler is determined. The velocity of the flow through the nozzle is computed by dividing the flow rate by the cross-sectional area of the nozzle flow passage entrance. The sediment flux is the product of the sediment concentration of the collected sample and the nozzle velocity.

Suspended sediment samplers are operated on the premise that the velocity of flow through the nozzle is equal to the velocity of the stream flow surrounding the nozzle (Beverage 1979). This condition is known as iso-kinetic sampling. For sediment sampling quality control, the nozzle velocity V_n and the stream flow velocity V_s are expressed as a ratio given by

$$K = \frac{V_n}{V_s} \tag{1}$$

where K is the sampler performance coefficient. For iso-kinetic conditions, $K = 1$ and it is assumed that the flow entering through the nozzle contains the same sediment-water mixture as the stream flow being sampled. When the suspended sediment is sand and $K > 1$, the sampler will under-sample the suspended sediment concentration, whereas when $K < 1$, the sampler will over-sample (Beverage 1979, Beverage and Futrell 1986). For a given flow velocity, errors in sample concentration become increasingly sensitive to the value of K as the particle size increases. For silts and clays, the sample concentration is less sensitive to K because the particles are more sensitive to the acceleration of the fluid and thus follow the fluid more closely.

The performance of the DH-59 sampler can be evaluated by examining the variation of K with towing velocity. The accuracy of a given sampler calibration is reflected by the uncertainty in the value of K at different towing velocities over its operating range. The sampler to sampler variability can be determined by comparing values of K for different DH-59 samplers for the same towing velocity. Finally, the effect of using different nozzles of a given size and type, can be determined by examining the change in the sampler performance coefficient.

3. EXPERIMENTAL EQUIPMENT AND PROCEDURE

3.1 Towing Tank

The towing tank used to test the sampler is 122 m long by 5 m wide and is constructed of reinforced concrete founded on piles. The full depth of the tank is 3 metres, of which 1.5 metres are below ground level. Normally the water depth is maintained at 2.7 metres. Concrete was chosen for its stability and to reduce possible vibrations and convection currents.

At one end of the tank is an overflow weir. Waves arising from towed objects and their suspensions are washed over the crest, thereby reducing wave reflections.

Parallel to the sides of the tank perforated beaches serve to dampen lateral surface wave disturbances.

3.2 Towing Carriage

The carriage is 3 metres long, 5 metres wide, weighs 6 tonnes and travels on four precision machined steel wheels. The carriage is operated in three overlapping speed ranges:

0.005 m/s - 0.06 m/s
0.05 m/s - 0.60 m/s
0.50 m/s - 6.00 m/s

The maximum speed of 6.00 m/s can be maintained for 12 seconds. Tachometer generators connected to the drive shafts emit a voltage signal proportional to the speed of the carriage. A feedback control system uses these signals as input to maintain constant speed during tests. The average speed data for the towing carriage is obtained by recording the voltage pulses emitted from a measuring wheel. This wheel is attached to the frame of the towing carriage and travels on one of the towing tank rails, emitting a pulse for each millimeter of travel. The pulses and measured time are collected and processed to produce an average towing speed with a micro computer data acquisition system. Analysis of the towing speed variability by Engel (1989), showed that for speeds between 0.20 m/s and 3.00 m/s, the error in the mean speed was less than 0.15% at the 99% confidence level. Occasionally, these tolerances are exceeded as a result of irregular occurrences such as "spikes" in the data transmission system of the towing carriage. Tests with such anomalies are recognized by the computer and are automatically abandoned.

3.3 The DH-59 Sampler

The sampler consists of a cast bronze housing, a 0.6 ℓ (pint) "milk bottle", and three teflon nozzles. The nozzles have an inside diameter of 6.4 mm (1/4"), 4.8 mm (3/16") and 3.2 mm (1/8"), each having geometric properties most suitable to the particular range of velocities shown in Table 1. The sampler and its appurtenances are shown in Figure 1.

The DH-59 sampler is designed to sample at velocity less than 2.5 m/s, suspended by a hand line in streams too deep to be waded. When the sampler is lowered into the flow, air is expelled through a 3.0 mm diameter air vent at the side of the sampler casing. The air vent outlet is located about 5 mm above the entrance of the nozzle flow passage. This creates a small, positive, net hydro-static pressure which is constant regardless of the depth of submergence of the sampler.

3.4 Selection of Test Nozzles

The nozzles were selected from samples tested by Engel (1991) using a new static test chamber, developed to determine the variability in the coefficient of velocity for suspended sediment sampler nozzles. Prior to testing, a nozzle was selected and fastened to the nozzle mount which was then secured in the base of the test chamber. The measurements consisted of the water level elevation above the nozzle entrance in the test chamber stilling well, the volume of water passing through the nozzle and the time required to pass that volume of water. For each value of static head, the discharge was measured by intercepting the outflow jet from the nozzle with a graduated cylinder and measuring the time to collect the water. The data were used to compute the velocity coefficient for each nozzle from the relationship

$$C_v = \frac{V_n}{V_t} \tag{2}$$

where C_v = the nozzle velocity coefficient, V_n = the flow velocity through the nozzle and V_t = the theoretical velocity of flow through the nozzle. The uncertainty in the velocity coefficients obtained with this method is less than 0.3% at the 95% confidence level (Engel 1990). Tests were conducted for each of the 25 nozzles of the three sizes of nozzles used with the DH-59 sampler, for a total of 75 tests.

To determine the uncertainty in the sampler calibrations, the nozzle having a velocity coefficient closest to the mean value for each sample of 25 nozzles was selected. This nozzle was designated as the "standard nozzle" because it was deemed to have the most representative properties of the nozzles used with the DH-59 sampler. These nozzles, were numbered S59-10 for the 3.2 mm diameter, S59-3 for the 4.8 mm diameter and S59-1 for the 6.4 mm diameter. Each nozzle was used with each of the 5 samplers tested.

To determine the effect of changing nozzles on the sampler performance coefficient K, the nozzle, for which the difference between its value of C_v and the mean value for the sample was the greatest, was selected. These nozzles were numbered S59-22 for the 3.2 mm diameter, S59-21 for the 4.8 mm diameter and S59-7 for the 6.4 mm diameter with deviations in the velocity coefficient C_v from the standard nozzles of 11.8 %, 12.4% and 8.7% respectively. Each of these nozzles was used only with one of five samplers.

3.5 General Test Procedure

For a given nozzle, the volume of water that can enter the sampler bottle in a given period of time should primarily depend on the physical properties of the nozzle and the air vent (Engel and Droppo 1990, Engel 1991 and Engel and Droppo 1992). In order to determine the uncertainty in the sampler performance coefficient, a series of tests, each repeated 10 times over the range of velocities specified in Table 1, was conducted. At the beginning of each series of tests, the nozzle was inserted into the sampler nose and the sampler assembled in its standard configuration.

Once the sampler was prepared, the towing carriage was set in motion. When the carriage had reached its preset constant velocity, the sampler was submerged and held at 0.2 m below the surface of the water for the set period of time given in Table 1. The filling times in Table 1 are the maximum allowable without over-filling the bottle, thereby ensuring that there is no interference in the air flow through the vent. The tests were conducted in a towing tank because this afforded better control over the reference velocity than can be obtained in a flume. It has been shown that there is little difference between sampler calibrations obtained in a flume and in a towing tank (Beverage and Futrell 1986). Although, this procedure does not simulate actual stream sampling methods, it does, however, allow the operation of a sampler at a constant velocity. When the set period of sampling time had expired, the sampler was removed from the water and the volume of water determined with a 1000 ml graduated cylinder. The velocity of flow through the sampler nozzle was then computed from the equation

$$V_n = \frac{1.273 V_w}{d^2 t_s} \tag{3}$$

where d = the diameter of the flow passage through the nozzle in mm, V_w = the volume of water collected in c.c., t_s = the time over which the sampler was submerged in seconds. Each test was repeated 10 times to obtain a sufficiently large sample to determine the mean values and the uncertainties in the sampler performance coefficient K. Each series of tests was begun at the lowest towing velocity given in Table 1 and continued at each subsequent velocity until the maximum was reached. The data for the five samplers are given in Table 2, 3 and 4 for the 3.2 mm, 4.8 mm and 6.4 mm nozzles respectively.

4. DATA ANALYSIS

4.1 Performance Coefficient of DH-59 Sampler

Values of the performance coefficient K from Table 2, 3 and 4 were plotted as K versus V for the five samplers, with the 3.2 mm, 4.8 mm and 6.4 mm standard nozzles in Figure 2, 3 and 4. Average curves were fitted to the plotted data to facilitate the analysis. Each of the three nozzles is used for a different velocity range as shown in Table 1. In the case of the 3.2 mm nozzle, the behaviour of the samplers is most consistent with values of K decreasing gradually from about 1.04 when $V = 1.0$ m/s to 0.96 when $V = 2.5$ m/s. This behaviour suggests that the sampler is operating under nozzle control when the 3.2 mm nozzles are used.

In contrast to this, the performance coefficients of the five samplers are less consistent when the 4.8 mm nozzle is used. This may be partly due to the fact that this nozzle is used for velocities as low as 0.30 m/s. The greatest scatter in the values of K occurs at this velocity. As velocities increase to 1.0 m/s, the values of K become more consistent and are very similar, decreasing from a value near 1.0 at $V = 1.2$ m/s to about 0.93 when $V = 1.8$ m/s. For values of $V \leq 1.0$ m/s, the sensitivity of K is dependent on the sampler used. This indicates that when the 4.8 mm nozzle is used, it may be necessary to identify each sampler to ensure that sampling errors are kept as small as possible.

When the 6.4 mm nozzle is used, the performance coefficients are the most sampler dependent. This is most significant for this nozzle because the sampling velocities are less than 1.0 m/s over its full operating range. Once again, values of K are most inconsistent at the minimum velocity of 0.30 m/s, with the variability decreasing as the velocity increases. When $V = 1.0$ m/s, all samplers are approximately iso-kinetic.

4.2 Uncertainty in the Value of K for a Particular Sampler

The true value of K, at a given velocity, for a particular sampler is the mean value of a very large sample, each determined experimentally under the same conditions. Such large samples are not feasible and values of K are inferred based on limited sample sizes. The true value of K is then said to lie between confidence limits defined by the relationship

$$\mu_K = \overline{K} \pm \frac{t_{0.975} S_K}{\sqrt{n-1}} \tag{4}$$

where μ_K = the mean value of K from a very large sample, $\overline{K}$ = the mean value of K from a limited sample, $t_{0.975}$ = the confidence coefficient at the 95% confidence level from Student's t distribution for $(n-1)$ degrees of freedom (Spiegel, 1961), S_K = the standard deviation of K about the sample mean $\overline{K}$ and n = the number of values of K composing the limited sample. Equation (4) can be made dimensionless by dividing both sides by $\overline{K}$. In addition, by denoting the coefficient of variation as C_K, then $C_K = \frac{S_K}{\overline{K}}$ and one obtains

$$\mu_K = 1 \pm \frac{t_{0.975} C_K}{\sqrt{n-1}} \tag{5}$$

The quantity $\frac{t_{0.975} C_K}{\sqrt{n-1}}$ in equation (5) represents the relative uncertainty in determining the true value of K at the 95% confidence level obtained for n different observations of K and may be expressed as

$$E_K = \frac{100t_{0.975}C_K}{\sqrt{n-1}} \tag{6}$$

where E_K = the relative uncertainty in percent. Values of E_K were computed from the test data for $n = 10$ and these are also given in Table 2, 3 and 4.

The values of E_K are presented in the form of bar graphs for the five samplers at the towing velocities used for the present tests in Figures 5, 6 and 7 for the 3.2 mm, 4.8 mm and 6.4 mm nozzles respectively. Results for the three sizes of nozzles used, at equal velocities, indicate that uncertainties are only marginally affected by nozzle size. Uncertainties are mainly affected by the towing velocity. Generally, the largest uncertainties occur at the lowest velocities and decrease as velocity increases. These characteristics vary from sampler to sampler, however, it is quite clear from the bar graphs, that the uncertainty in determining K, for a given sampler, is always less than 3% which can be considered to be quite low.

4.3 Uncertainty in the Value of K for a Group of Samplers

Average values of K for the five samplers tested, given as $\overline{K_s}$ and the uncertainties in determining these average values given as E_s were computed for each of the three sizes of nozzles and the corresponding towing velocities and are given in Table 5. These values of E_s are superimposed on the bar graphs in Figures 5, 6 and 7. It can be seen that, in all cases, $E_s > E_K$ and that $E_s < 5\%$ when $V \geq 0.90$ m/s. For small values of velocity, E_s was largest, having values of 13.2% and 17.7% for the 4.8 mm and 6.4 mm nozzles respectively when the velocity is 0.30 m/s. Generally, values of E_s tend to decrease as velocities increase from 0.30 m/s to 0.90 m/s.

When the 3.2 mm nozzle is used, values of E_s are always less than 5% and therefore, a calibration of any given sampler is valid for any other sampler with an uncertainty of less than 5% at the 95% confidence level. When the 4.8 mm and 6.4 mm nozzles are used, values of E_s are in excess of 5% for velocities at least up to 0.75 m/s as shown in Figures 6 and 7. These high values of E_s can be attributed to differences in the sampler air vent system because the flow rate into the sampler is controlled by the air vent. These problems can be reduced by adjusting the air vent size to increase or decrease the air flow resistance (Engel, 1991). Samplers should be checked to ensure that each has an acceptable value of performance coefficient when the 4.8 mm and 6.4 mm nozzles are used.

4.4 Effect of Changing Nozzles

An important consideration is the effect that different nozzles of the same type and size may have on the performance coefficient of the DH-59 sampler because of small differences as a result of fabrication variances. It would be of great operational advantage, if small variations in the geometric properties of nozzles do not significantly alter the value of the performance coefficient. If this is the case, then individual calibrations with a particular nozzle will not be necessary. In addition, it will be possible to exchange nozzles in the field without compromising the performance of a given sampler. Data on the effects of changing nozzles are given in Tables 6, 7 and 8 for the 3.2 mm, 4.8 mm and 6.4 mm nozzles respectively.

The mean values of K obtained with sampler No. A06550 (No.1) and the 3.2 mm nozzle No. S59-22 from Table 6 were plotted in Figure 8 with the results for the same sampler, used with the standard nozzle No. S59-10 from Table 2. Smooth curves were drawn through the plotted points to facilitate the analysis. The curves show that differences in values of K for the two nozzles are virtually constant over the full operating range. This means that the sampler is operating under nozzle control and therefore, the differences in the performance coefficient are due to differences in the nozzle geometry. The differences in K for the two nozzles is of the order of 20% and therefore is quite significant. Nozzle No. S59-22 has a velocity coefficient C_v which deviates from that for the standard nozzle No. S59-10, by 11.8%. This effect of the velocity coefficient confirms that the sampler is operating under nozzle control when the 3.2 mm nozzle is used. Therefore, for best sampling results, care should be taken that 3.2 mm nozzles, with velocity coefficient values close to that of the standard nozzle, are used.

Values of K obtained with sampler No. 124327-7 (No.2) and the 4.8 mm nozzle No. S59-21 from Table 7 were plotted in Figure 9 with the results for the same sampler, used with the standard nozzle No. S59-3 from Table 3. The plot shows virtually no difference in K for the two nozzles. The fact that these results were obtained with two nozzles, having velocity coefficients which differed by 12.4%, suggests that the sampler is operating under vent control. Under such conditions, minor differences in nozzle geometry do not affect the sampler performance. Therefore, different 4.8 mm nozzles can be used with a given sampler without significant loss in sampling accuracy at the 95% confidence level.

Finally, values of K obtained with sampler No. 124327-7 (No.2) and the 6.4 mm nozzle No. S59-7 from Table 8 were plotted in Figure 10 with the results for the same sampler, used with the standard nozzle No. S59-1 from Table 4. The difference in the velocity coefficient was 8.7%. The plot shows even less difference in K for the two nozzles than was observed with the 4.8 mm nozzles. This is again indicative of the sampler operating under vent control and therefore, minor differences in nozzle geometry do not affect the sampler performance. As a result, different 6.4 mm nozzles can be used with a given sampler without significant loss in sampling accuracy at the 95% confidence level as long as good quality control on the nozzle fabrication is maintained.

5. CONCLUSIONS

Tests, conducted in a towing tank, on the DH-59 suspended sediment sampler with selected 3.2 mm, 4.8 mm and 6.4 mm nozzles have resulted in the following conclusions:

The performance of the DH-59 sampler was closest to being iso-kinetic when the 3.2 mm nozzle was used. For the five samplers tested, values of K varied between 1.04 and 0.93 for velocities between 1.0 m/s and 2.5 m/s. When the 4.8 mm nozzle was used, values of K were positive for velocities less than 1.10 m/s and negative for velocities greater than 1.10 m/s. When the 6.4 mm nozzle is used, values of K were greater than 1.0 for all velocities over the normal operating range. Values of K decreased as velocities increased.

The calibration of a given DH-59 sampler was repeatable within 3% at the 95% confidence level when the 3.2 mm, 4.8 mm and 6.4 mm nozzles were used.

The variability in performance coefficient from sampler to sampler, for a given nozzle size, was greater than the uncertainty in the calibration of any single sampler. The difference was least when the 3.2 mm nozzle was used and increased as the nozzle size was increased to 4.8 mm and 6.4 mm.

The uncertainty in the performance coefficient from sampler to sampler was less than 5% at the 95% confidence level when the 3.2 mm nozzle was used. When the 4.8 mm and 6.4 mm nozzles were used, the uncertainty increased above 5% for velocities less than about 0.9 m/s. The largest uncertainty of 18% was obtained with the 6.4 mm nozzle at its lowest operating velocity of 0.3 m/s. Therefore, each sampler should be checked for use with the 4.8 mm and 6.4 mm nozzles to ensure that satisfactory performance coefficients are obtained.

The use of different nozzles of the same type and size significantly affected the performance of the DH-59 sediment sampler when the 3.2 mm nozzles were used. Therefore, 3.2 mm nozzles of the type prescribed for use with the DH-59 sampler should be checked to ensure that their velocity coefficients are, sufficiently similar to that of the standard 3.2 mm nozzle.

The use of different nozzles of the same type and size did not significantly affect the sampler performance when the 4.8 mm and 6.4 mm nozzles were used. Therefore, such nozzle sizes of the type prescribed for use with the DH-59 sampler, can be interchanged without further calibration.

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TABLE 1   Towing Velocities and Sampling Durations

Nozzle [mm]	V $[m/s]$	Time $[s]$
3.2	1.00	38
	1.20	33
	1.50	28
	1.80	25
	2.10	20
	2.50	16
4.8	0.30	35
	0.60	30
	0.90	22
	1.20	16
	1.50	12
	1.80	10
6.4	0.30	33
	0.45	21
	0.60	16
	0.75	12
	1.00	09

TABLE 2 **Test Data for Standard 3.2 mm Nozzle (No. S59-10)**

Test	V $[m/s]$	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	1.00	1.0324	0.01012	0.738	A06550 (No. 1)
2	1.20	0.9894	0.00658	0.501	
3	1.50	0.9654	0.00913	0.712	
4	1.80	0.9462	0.01484	1.182	
5	2.10	0.9646	0.01362	1.064	
6	2.50	0.9341	0.01955	1.577	
1	1.00	0.9871	0.00846	0.646	124327-7 (No. 2)
2	1.20	0.9575	0.00618	0.486	
3	1.50	0.9566	0.00669	0.527	
4	1.80	0.9534	0.00603	0.476	
5	2.10	0.9522	0.00814	0.644	
6	2.50	0.9537	0.01075	0.849	
1	1.00	1.0420	0.00436	0.315	A35474 (No. 3)
2	1.20	0.9950	0.00729	0.552	
3	1.50	0.9669	0.00741	0.577	
4	1.80	0.9637	0.00971	0.759	
5	2.10	0.9866	0.01386	1.058	
6	2.50	0.9670	0.01104	0.860	
1	1.00	1.0548	0.01688	1.206	B23980 (No. 4)
2	1.20	1.0299	0.00641	0.469	
3	1.50	0.9978	0.01266	0.956	
4	1.80	0.0792	0.00857	0.659	
5	2.10	0.9708	0.00745	0.578	
6	2.50	0.9868	0.01579	1.205	
1	1.00	1.0760	0.01029	0.720	252187 (No. 5)
2	1.20	1.0399	0.00660	0.478	
3	1.50	1.0075	0.00881	0.659	
4	1.80	1.0000	0.00978	0.737	
5	2.10	0.9816	0.01239	0.951	
6	2.50	0.9900	0.02086	1.587	

Standard Nozzle (S59-10) is the nozzle for which the value of C_v is closest to the mean of a sample of 25 nozzles of the same size and type as determined by Engel (1991).

TABLE 3 Test Data for Standard 4.8 mm Nozzle (No. S59-3)

Test	V $[m/s]$	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	0.30	1.2744	0.02515	1.487	A06550 (No. 1)
2	0.60	1.1137	0.01431	0.968	
3	0.90	1.0754	0.01139	0.798	
4	1.20	0.9896	0.00912	0.694	
5	1.50	0.9423	0.00777	0.621	
6	1.80	0.9187	0.00762	0.625	
1	0.30	1.0375	0.02984	2.167	124327-7 (No. 2)
2	0.60	0.9988	0.01224	0.923	
3	0.90	1.0276	0.01097	0.804	
4	1.20	0.9497	0.00913	0.724	
5	1.50	0.9257	0.01075	0.875	
6	1.80	0.8989	0.00882	0.739	
1	0.30	1.1677	0.03439	2.219	A35474 (No. 3)
2	0.60	1.0422	0.01180	0.853	
3	0.90	1.0354	0.00713	0.519	
4	1.20	0.9782	0.00770	0.593	
5	1.50	0.9147	0.00883	0.727	
6	1.80	0.9127	0.01232	1.017	
1	0.30	1.3245	0.02677	1.523	B23980 (No. 4)
2	0.60	1.0988	0.01791	1.228	
3	0.90	1.0612	0.01736	1.232	
4	1.20	0.9936	0.01063	0.806	
5	1.50	0.9494	0.01145	0.909	
6	1.80	0.9297	0.00828	0.671	
1	0.30	1.2945	0.02453	1.428	232187 (No. 5)
2	0.60	1.1121	0.01585	1.074	
3	0.90	1.0783	0.01907	1.332	
4	1.20	1.0012	0.01129	0.850	
5	1.50	0.9698	0.00753	0.585	
6	1.80	0.9499	0.01998	1.584	

Standard Nozzle (S59-3) is the nozzle for which the value of C_v is closest to the mean of a sample of 25 nozzles of the same size and type as determined by Engel (1991).

TABLE 4 Test Data for Standard 6.4 mm Nozzle (No. S59-1)

Test	V [m/s]	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	0.30	1.2336	0.01788	1.092	A06550 (No. 1)
2	0.45	1.1569	0.03419	2.226	
3	0.60	1.1004	0.01502	1.028	
4	0.75	1.0830	0.01648	1.146	
5	1.00	1.0210	0.01675	1.236	
1	0.30	0.9093	0.03158	2.616	124327-7 (No. 2)
2	0.45	1.0084	0.01269	0.948	
3	0.60	1.0149	0.00703	0.522	
4	0.75	1.0080	0.00920	0.688	
5	1.00	0.9801	0.00906	0.696	
1	0.30	1.0967	0.01831	1.258	A35474 (No. 3)
2	0.45	1.0557	0.02721	1.942	
3	0.60	1.0597	0.01541	1.095	
4	0.75	1.0668	0.01649	1.164	
5	1.00	0.9571	0.01011	0.781	
1	0.30	1.2503	0.02463	1.484	B23980 (No. 4)
2	0.45	1.1699	0.01898	1.222	
3	0.60	1.2151	0.02106	1.268	
4	0.75	1.1004	0.01118	0.765	
5	1.00	1.0281	0.01601	1.173	
1	0.30	1.2338	0.04263	2.603	252187 (No. 5)
2	0.45	1.1782	0.02141	1.369	
3	0.60	1.1274	0.01029	0.688	
4	0.75	1.1220	0.01245	0.836	
5	1.00	1.0340	0.01898	1.383	

Standard Nozzle (S59-1) is the nozzle for which the value of C_v is closest to the mean of a sample of 25 nozzles of the same size and type as determined by Engel (1991).

TABLE 5 Test Data for Sampler to Sampler Variability

Test	V $[m/s]$	$\overline{K_s}$	S_s	E_s [%]	Nozzle Size
1	1.00	1.0385	0.03303	4.421	3.2 mm (S59-10)
2	1.20	1.0023	0.03318	4.601	
3	1.50	0.9788	0.02235	3.174	
4	1.80	0.9685	0.02154	3.091	
5	2.10	0.9712	0.01369	1.959	
6	2.50	0.9663	0.02334	3.357	
1	0.30	1.2197	0.11776	13.420	4.8 mm (S59-3)
2	0.60	1.0731	0.05076	6.575	
3	0.90	1.0556	0.02308	3.039	
4	1.20	0.9824	0.02011	2.845	
5	1.50	0.9404	0.02136	3.157	
6	1.80	0.9220	0.01916	2.889	
1	0.30	1.447	0.14553	17.672	6.4 mm (S59-1)
2	0.45	1.138	0.07687	9.953	
3	0.60	1.0855	0.04795	6.140	
4	0.75	1.0760	0.04321	5.582	
5	1.00	1.0077	0.02788	3.846	

TABLE 6 Test Data for 3.2 mm Nozzle (No. S59-22)

Test	V $[m/s]$	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	1.00	1.1923	0.01234	0.780	A06550 (No. 1)
2	1.20	1.1514	0.01115	0.730	
3	1.50	1.1084	0.01072	0.729	
4	1.80	1.0883	0.01055	0.730	
5	2.10	1.1141	0.01591	1.076	
6	2.50	1.0932	0.02776	1.913	

TABLE 7 Test Data for 4.8 mm Nozzle (No. S59-21)

Test	V $[m/s]$	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	0.30	0.9430	0.03033	2.423	124327-7 (No. 2)
2	0.60	1.0081	0.01322	0.988	
3	0.90	1.0238	0.01115	0.820	
4	1.20	1.0005	0.00817	0.615	
5	1.50	0.9958	0.00720	0.545	
6	1.80	0.9649	0.01498	1.170	

TABLE 8 Test Data for 6.4 mm Nozzle (No. S59-7)

Test	V $[m/s]$	$\overline{K}$	S_K	E_K [%]	Sampler No.
1	0.30	0.8781	0.02496	2.141	124327-7 (No. 2)
2	0.45	0.9684	0.01475	1.147	
3	0.60	0.9819	0.00938	0.720	
4	0.75	0.9846	0.00491	0.376	
5	1.00	0.9575	0.01127	0.887	

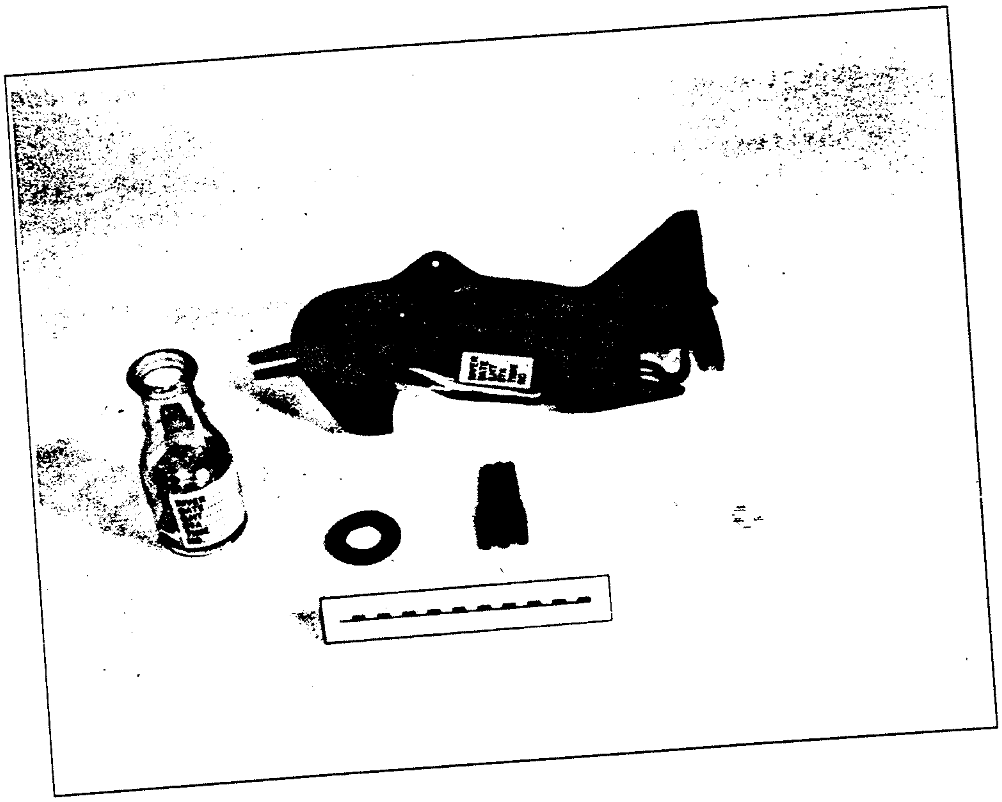

Figure 1. Depth-integrating hand-line sampler, US DH-59.

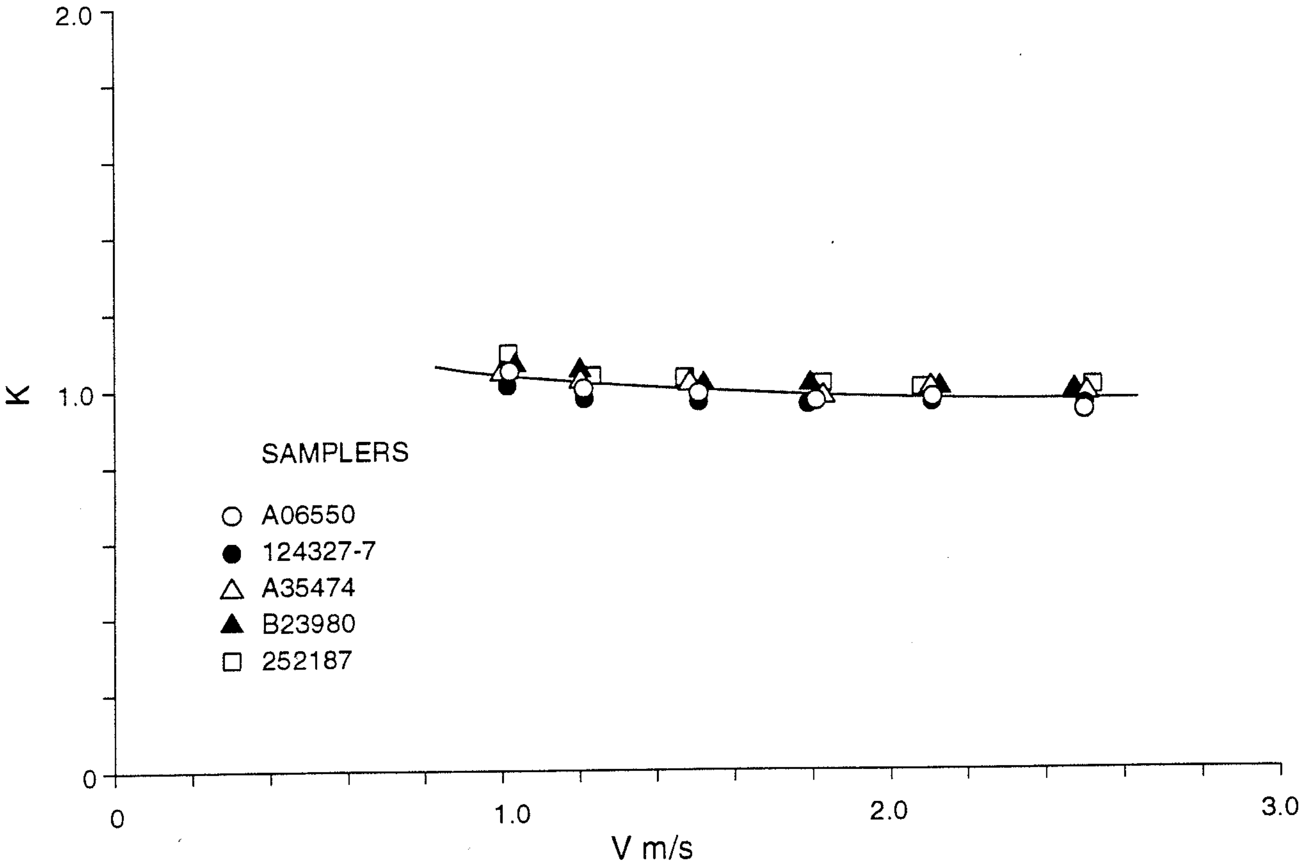

Figure 2. Variation of K with towing velocity when 3.2 mm nozzle is used.

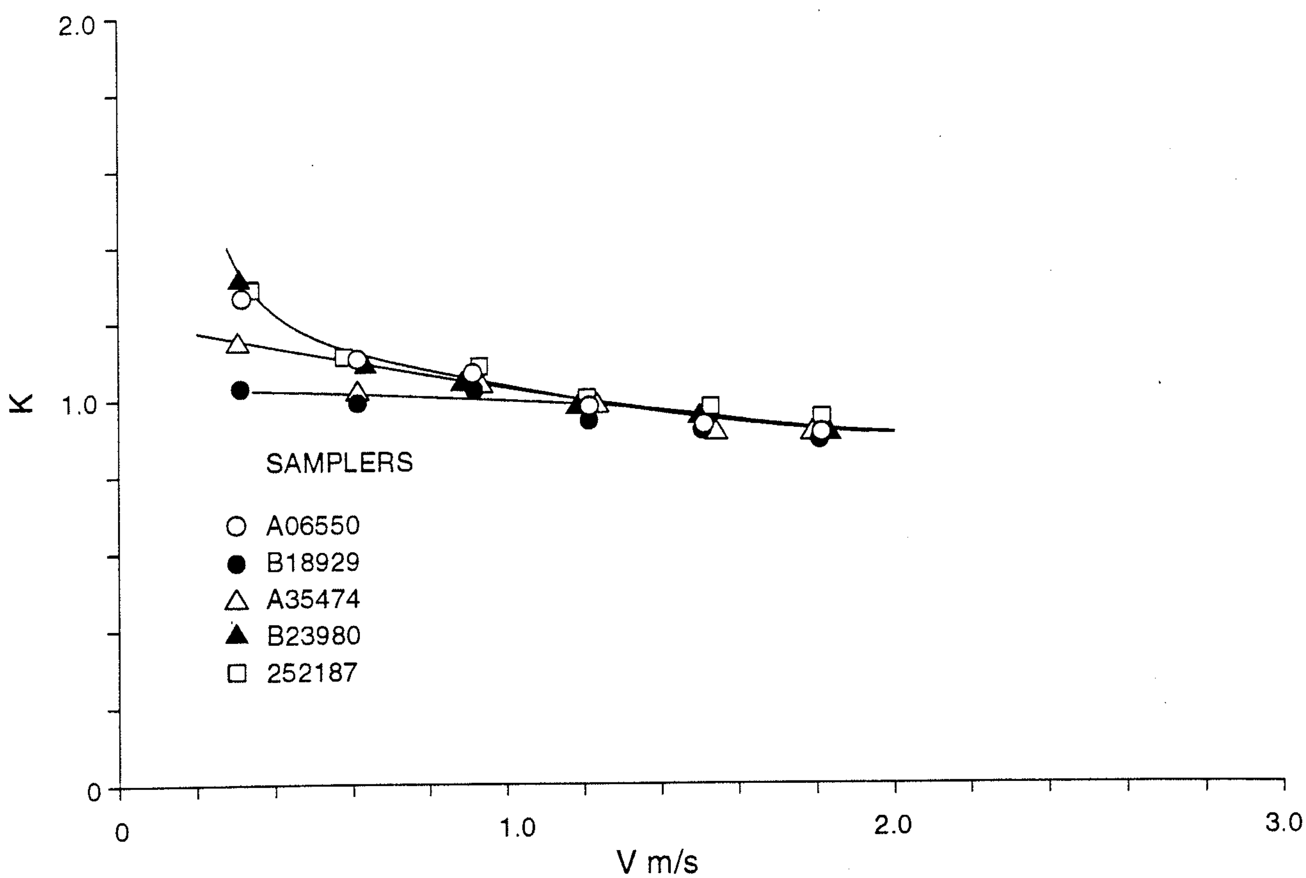

Figure 3. Variation of K with towing velocity when 4.8 mm nozzle is used.

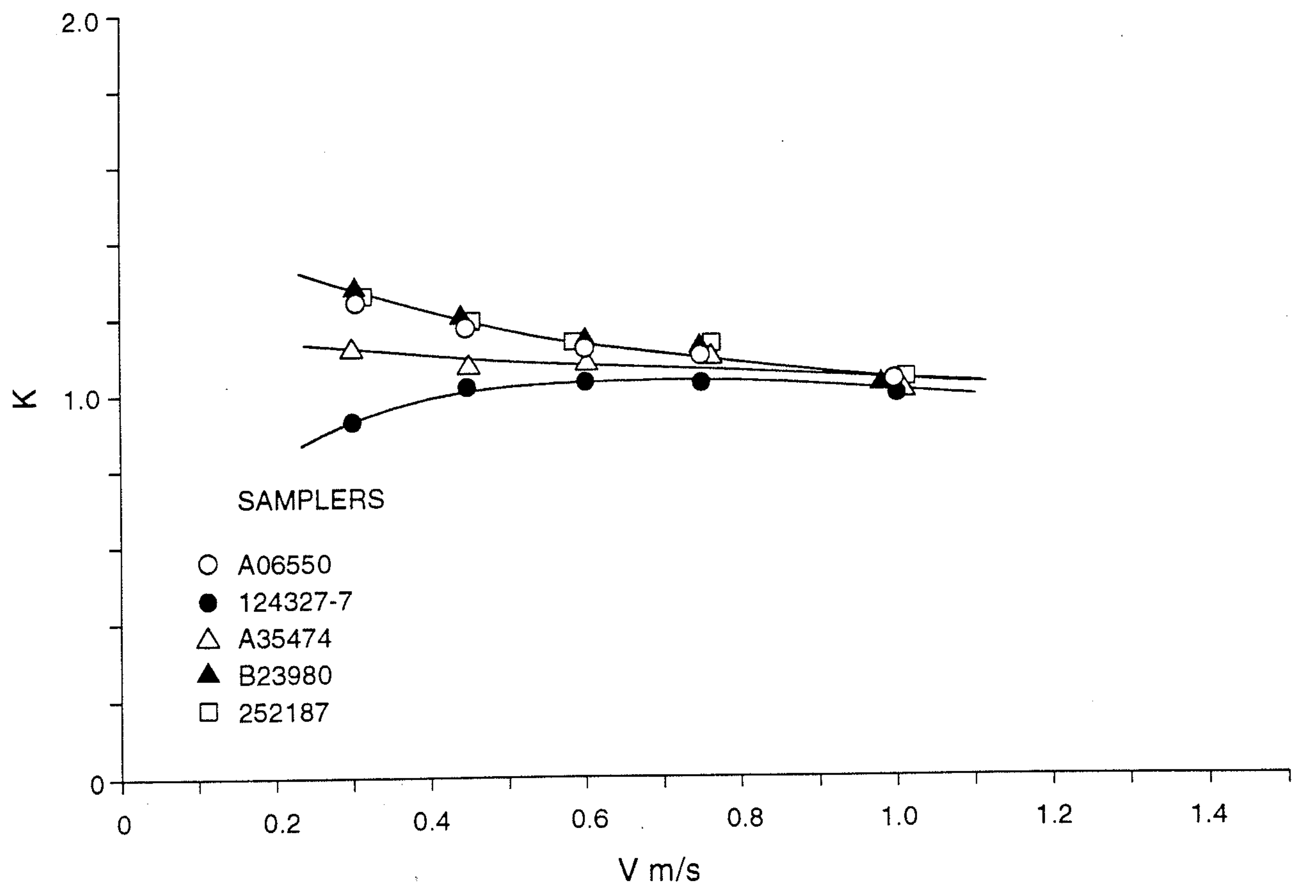

Figure 4. Variation of K with towing velocity when 6.4 mm nozzle is used.

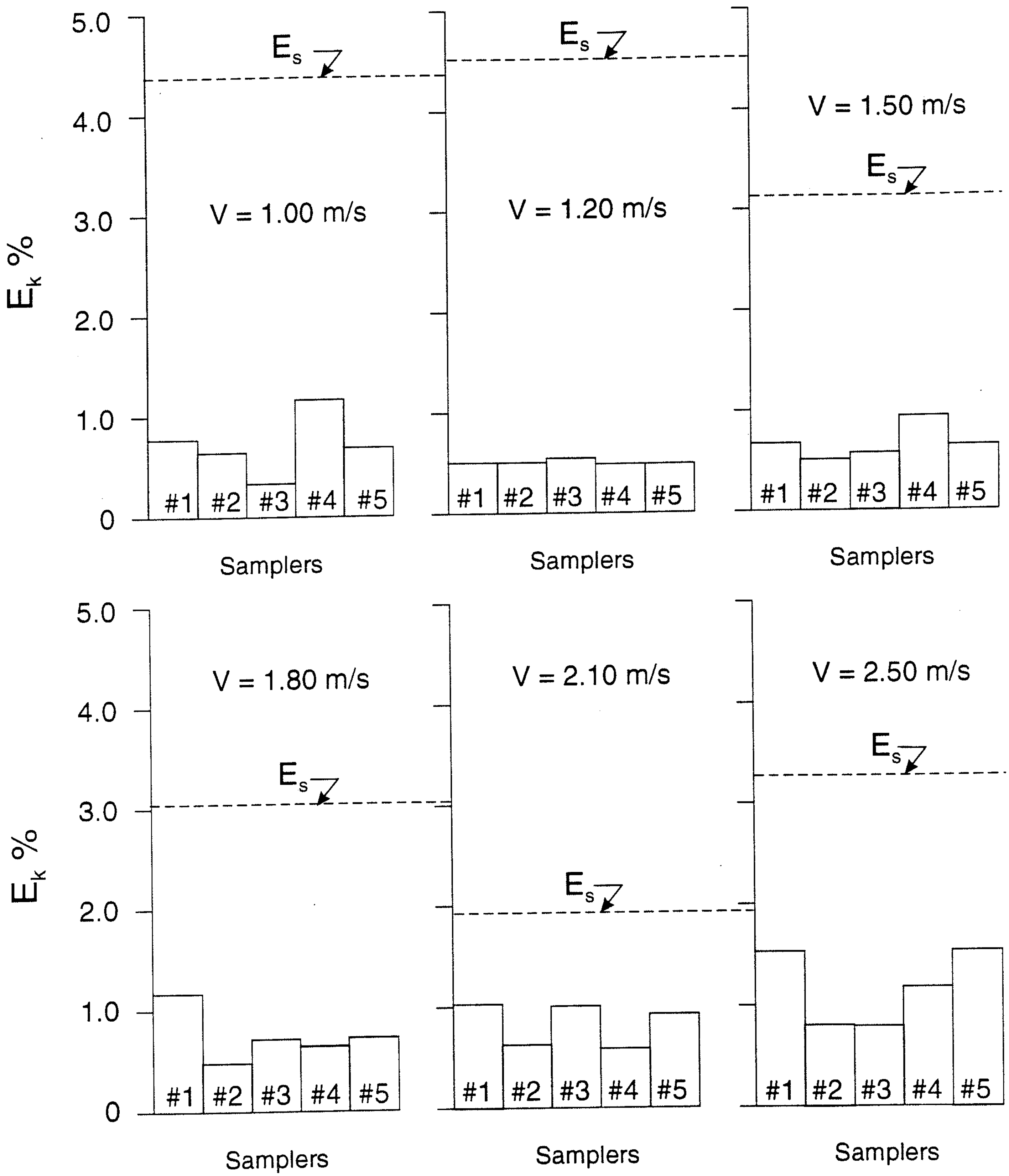

Figure 5. Uncertainty in K with 3.2 mm nozzle at 95% confidence level.

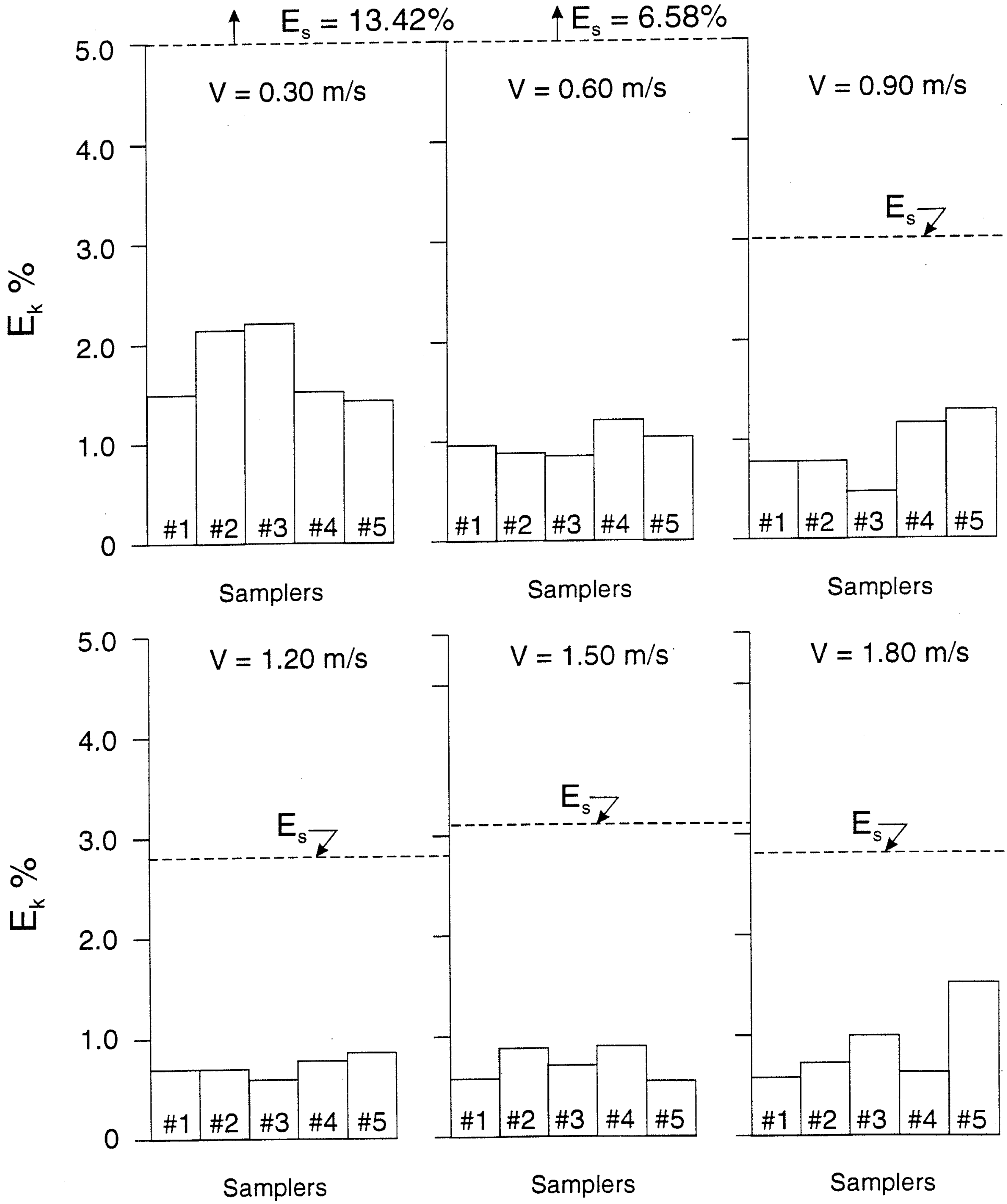

Figure 6. Uncertainty in K with 4.8 mm nozzle at 95% confidence level.

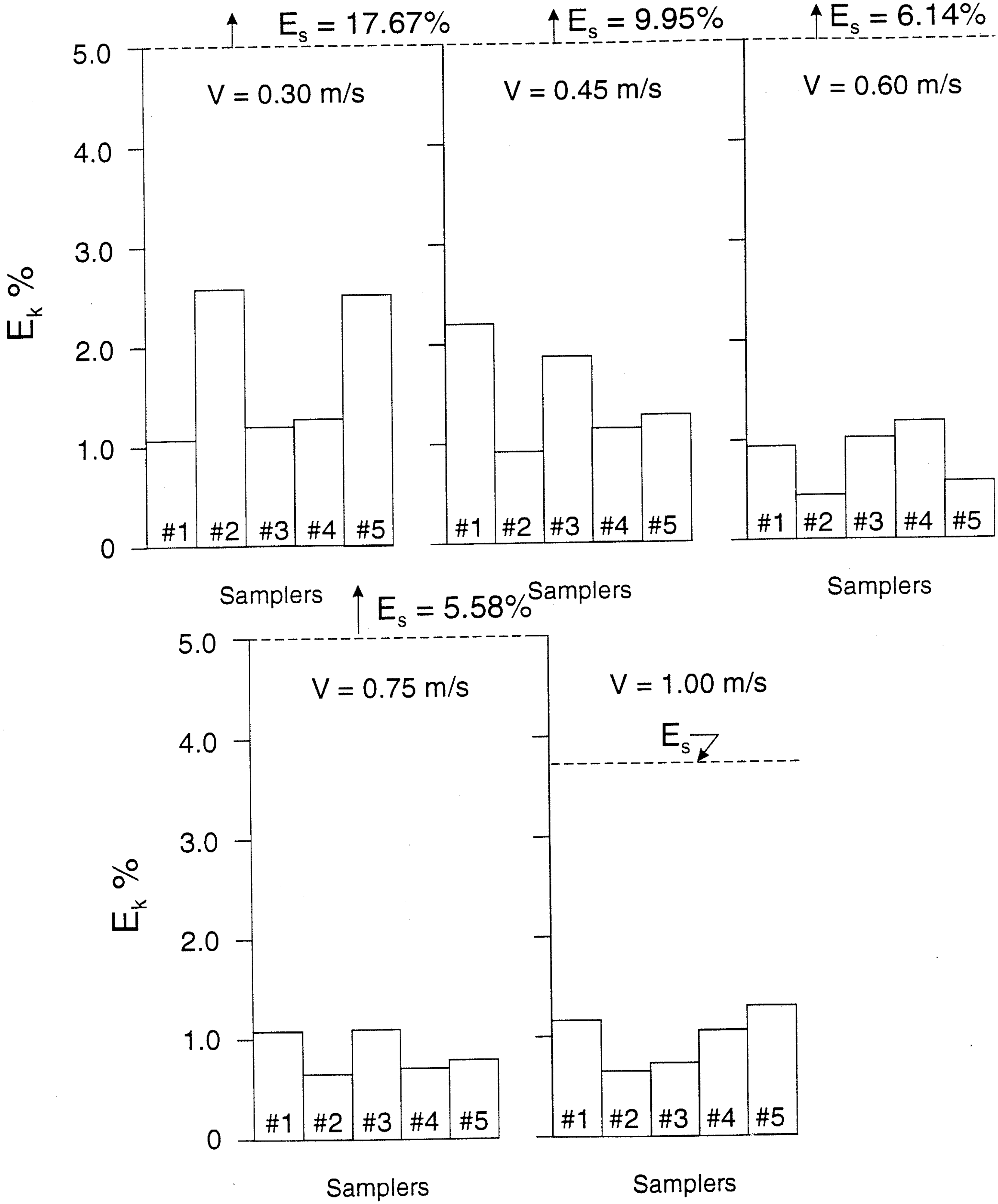

Figure 7. Uncertainty in K with 6.4 mm nozzle at 95% confidence leve

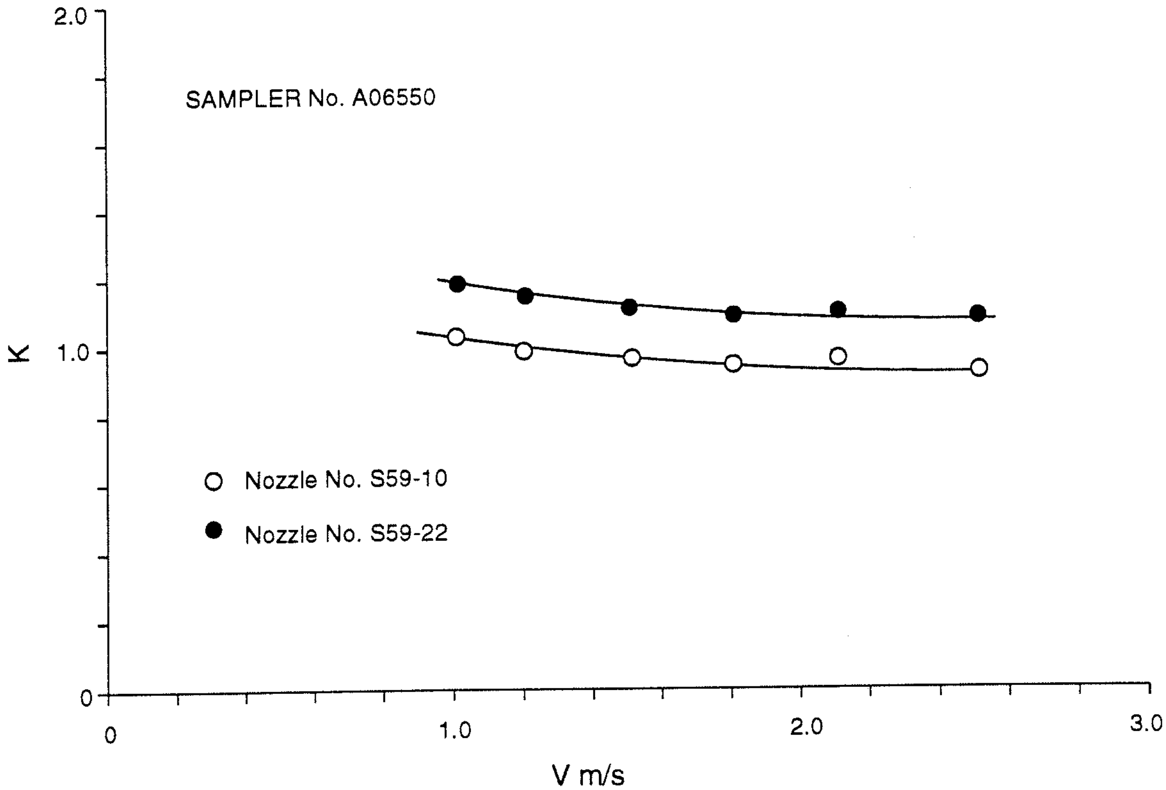

Figure 8. Effect of changing nozzles on K when 3.2 mm nozzle is used.

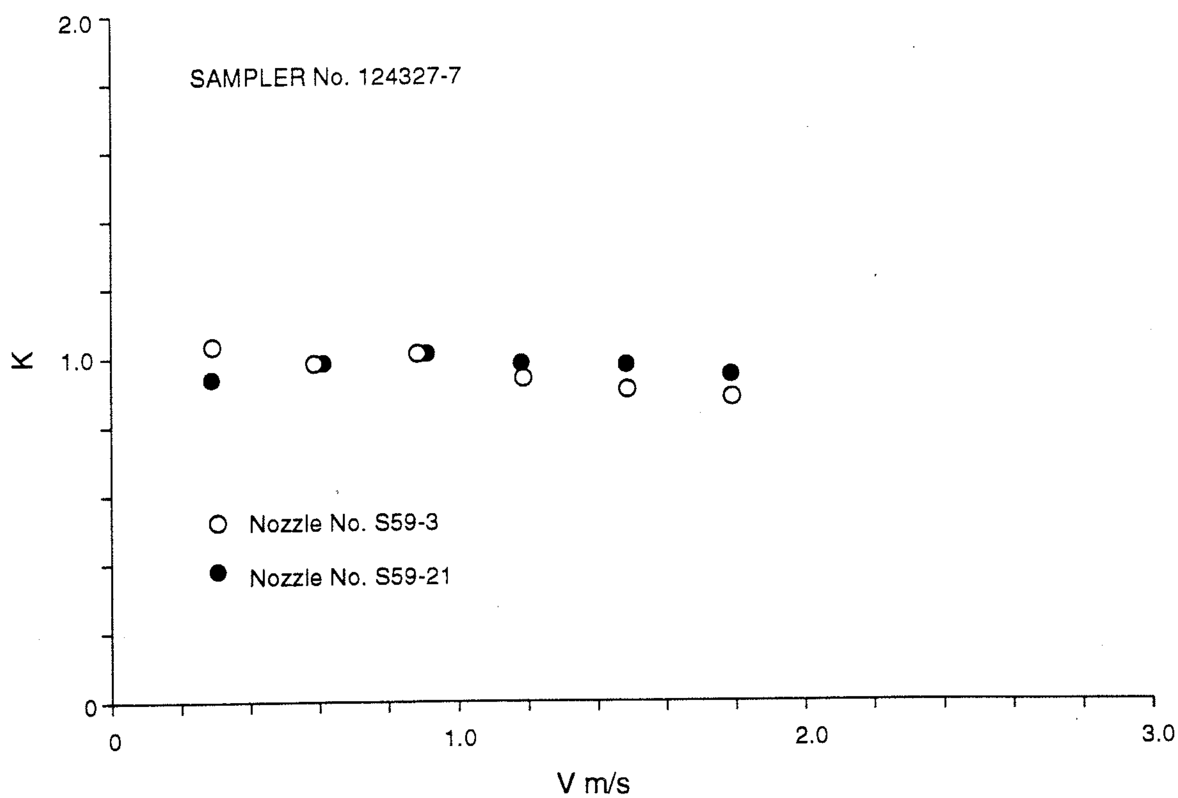

Figure 9. Effect of changing nozzles on K when 4.8 mm nozzle is used.

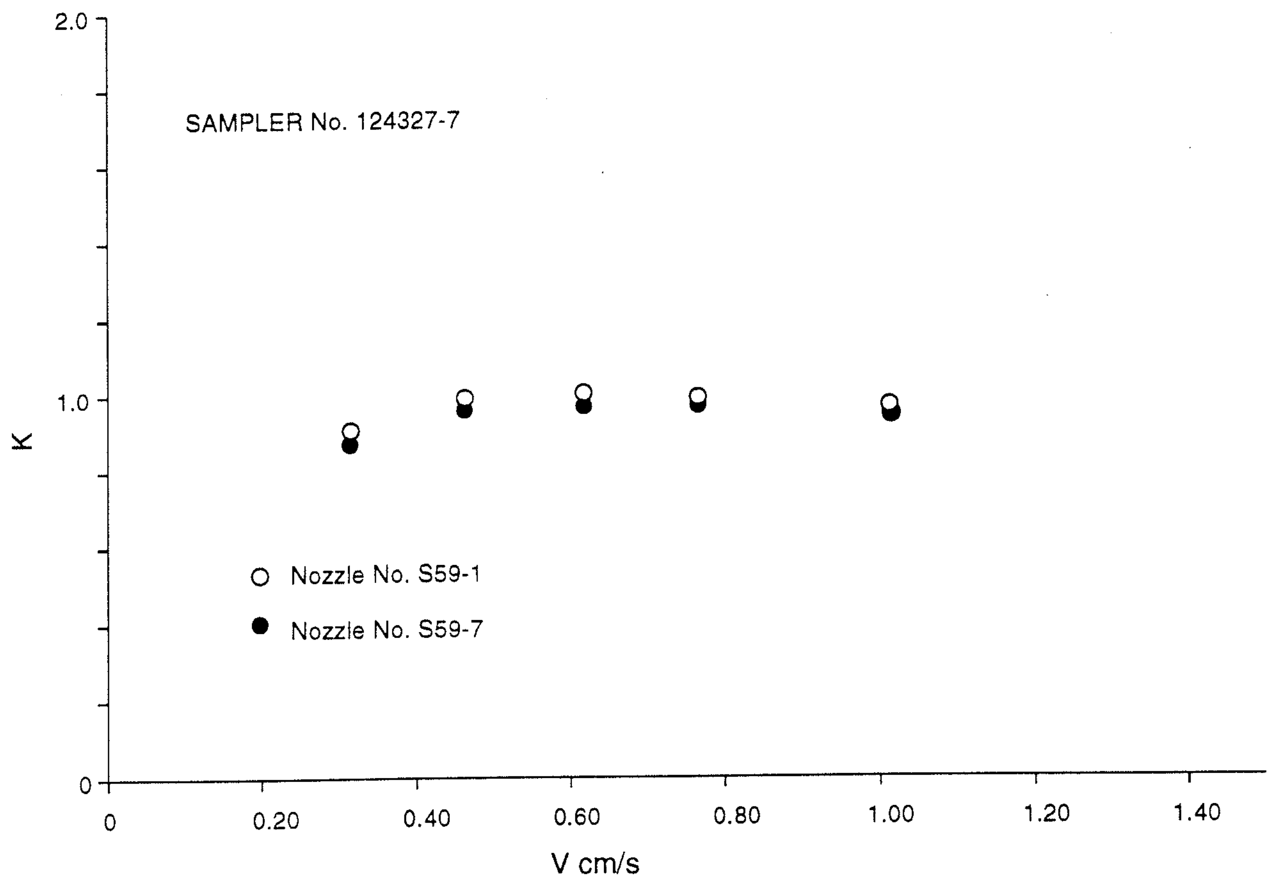

Figure 10. Effect of changing nozzles on K when 6.4 mm nozzle is used.