Evaluation of Four Fast-Response Flow Measurement Devices

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EVALUATION OF FOUR FAST RESPONSE FLOW MEASUREMENT DEVICES

by

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ABSTRACT

The Federal Mine Safety and Health Act of 1977 requires that sampling of dust in coal mine environments be conducted with an approved sampler operating at a flow rate of 2.0 liters of air per minute or at such other flow rate as prescribed by the Secretaries of Labor and of Health and Human Services. Standard procedures for calibration of these samplers within the Mine Safety and Health Administration utilize either a 3.0 liter capacity wet test meter or a 1.0 liter soap film calibrator. Several new flow calibrating devices have become commercially available. This paper describes an evaluation conducted on four such devices: the Mast Model 823-2 bubble flowmeter, the Buck Calibrator, the Kurz Model 541S mass flowmeter and the Kurz Pocket Calibrator. The precision of a series of measurements made with each instrument was compared to the precision of a series of measurements made with the wet test meter. The comparison showed that the variability of calibration measurements obtained with the fast response flow calibrators was between 1.5 and 4.5 times larger than that obtained with the WTM; however, with all of the calibration devices evaluated, three repetitive measurements were sufficient to obtain a precision of ±0.1 liters per minute.

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INTRODUCTION

When calibrating pump flowmeters used in respirable coal mine dust personal sampling units, personnel of the Mine Safety and Health Administration (MSHA) use a 3.0 liter capacity wet test meter (WTM) or a 1.0 liter capacity soap film calibrator. With either device, it is necessary to use an external timing device to determine the rate of flow[4]. In order to minimize errors resulting from imperfect timing, the time required for the WTM pointer to make at least three full revolutions (nine liters) is measured. With the soap film calibrator, the time it takes a soap film to move between two calibration marks is measured twice. The average of the two measurements is used to calculate the rate of flow. These procedures assure (with 95 percent confidence) that, at a rotometer calibration of 2.0 L/min, the flow rate will be between 1.9 and 2.1 L/min (±5 percent).

Recently several new calibrators have become commercially available. These devices allow for a more rapid measurement of flow rate without requiring ancillary equipment such as a timer. Because these devices offer potential time (manpower) saving advantages to MSHA, several were obtained and their precision of calibration evaluated. The calibrators evaluated were: the Mast Model 823-2 bubble flowmeter[5] (Mast Development Company, Air Monitoring Division), a 0.313 liter capacity soap film calibrator with a built-in automatic timer reading to 0.001 seconds; the Buck Calibrator (Gilian Instrument Corporation), also a soap film calibrator with automatic timer and circuitry which gives direct readout of flow rate; and two instruments manufactured by Kurz Instruments, Inc. The Kurz instruments, the Model 541S and the pocket calibrator, measure mass rather than volume flow rate with the flow rate being read from the position of a pointer on a scale marked in 0.1 L/min increments.

The Gilian and Mast instruments have been defined as primary standards[6] because they measure volume on the basis of the physical dimensions of an enclosed space. The WTM and Kurz instruments are considered secondary standards because they are instruments which trace their calibration to primary standards. Secondary standards normally require periodic calibration and adjustment, while primary standards, as defined here, require no adjustment.

The purpose of this study was to compare the precision of flow rate measurements obtained with the four fast response devices to that obtained with the WTM. The WTM was chosen as the basis for comparison because it is one of the two flow calibrators used by MSHA and has been the standard reference calibrator within MSHA's Coal Mine Safety and Health Activity.

EXPERIMENTAL PROCEDURES

One instrument of each type was available for this evaluation. The WTM was calibrated using a 0.1 cubic foot standard bottle calibrated by the National Bureau of Standards. Both Kurz instruments were calibrated using a critical orifice, whose flow rate of 2 L/min was determined by measurement with the WTM. Thus, the calibration of all of the secondary standards was traceable to the 0.1 cubic foot bottle. To determine the precision of flow rate measurement with each device, series of 30 measurements were made with each device on 10 different days spaced over an 8-week period. Since the Kurz instruments continually display the flow rate, the 30 readings each day with these instruments were taken randomly during a 20-minute period.

The airflow measured with the different devices was maintained constant using a 2.0 L/min critical orifice. Since volumetric flow rate through a critical orifice varies with air temperature, upstream air pressure and density, pressure and psychrometric wet and dry bulb temperature measurements were obtained at the time of each series of measurements and used to calculate any change in flow rate relative to that measured initially. A schematic of the experimental setup is shown in Figure 1.

Flow rates obtained with the WTM were determined by measuring the time it took nine liters of air to pass through the WTM. A stopwatch was used to measure the time to 0.01 seconds; however, if the timer reading was between two digits, an estimate of the time was made to 0.005 seconds. At a flow rate of about 2 L/min this allows discrimination of the flow rate to about 0.002 L/min; i.e., the flow rate could be calculated to be 2.00 L/min, or 1.998 L/min, or 2.002 L/min, but not 1.999 L/min or 2.001 L/min. The calculated flow rates were noted to two decimal places.

The Mast bubble flowmeter has an automatic digital timer which reads to 0.001 seconds. This allows discrimination of the calculated flow rate to about 0.0002 L/min; however, measured flow rates were noted only to three decimal places. The Buck calibrator has direct readout of flow rate to 0.001 L/min. The two Kurz flow calibrators have analog meters marked with 0.1 L/min divisions. The Model 541S has a large enough scale to permit the flowrate to be estimated to 0.025 L/min, while estimates with the pocket calibrator are limited to 0.05 L/min. The flow rates measured with these instruments were noted to one decimal place.

TREATMENT OF DATA

The means ($\bar{x}$) and standard deviations (s) of the 10 sets of 30 measurements made with each instrument were calculated using normal statistics. Also calculated were the mean, standard deviation and coefficient of variation ($s/\bar{x} \times 100$) of the 10 average flow rate values obtained with each instrument.

Because mass flow rate through a critical orifice is affected by variation in the pressure upstream of the orifice and by density and temperature changes of the air[7], the average volumetric flow rates established from the

30 repetitive measurements obtained with the wet test meter were corrected to the conditions during test one using the relationship:

$$Q_c = Q_m \left(\frac{P_1 \quad \rho_i \quad T_i^{1/2}}{P_i \quad \rho_1 \quad T_1^{1/2}} \right)$$

where Q_c = Volumetric flow through the orifice corrected to the temperature, pressure and air density conditions of the first set of measurements.

Q_m = Volumetric flow through the orifice measured with the wet test meter.
P_1 = Atmospheric pressure during first set of measurements.
ρ_1 = Density of air during first set of measurements.
T_1 = Absolute temperature during first set of measurements.
P_i, ρ_i, T_i = Pressure, density and absolute temperature measurements during successive tests.

Instrument calibration biases and the precision of flow rate measurements, as compared to the WTM, were evaluated by statistically comparing the means and variances determined from the 10 mean values for each instrument to the mean and variance established for the corrected volumetric flow rates through the WTM. Calibration bias and precision difference were tested at the five percent level of significance using the "t" and "F" tests, respectively. The average variability associated with calibrations obtained with the respective devices was used to establish the number of repetitive measurements required to obtain a calibration, with 95 percent confidence, to within 0.1 L/min. The average variability was determined using the following formula:

$$\left(\frac{\Sigma s^2}{n} \right)^{1/2}$$

RESULTS AND DISCUSSION

The mean and standard deviation for each test run of 30 flow rate measurements with each device are shown on Table 1. Also shown on this table are the mean, standard deviation and coefficient of variation of the mean values obtained from the 10 tests. The measurements obtained with the Buck Calibrator on the same days as the other four instruments were found to be inaccurate due to misalignment of the flow tube and obtaining measurements with poorly shaped soap films. Therefore, the series of measurements shown for the Buck Calibrator were not made under the same environmental conditions as the other four instruments.

Statistical comparison of the mean flow rate values, determined from averaging the individual test means, using the "t" test showed that only measurements made with the Buck Calibrator were biased. The bias was approximately 1.4 percent. A comparison of the respective CV's with that established for the WTM measurements shows that the between-test variability for the other instruments was approximately 1.5 to five times that obtained with the WTM. However, the maximum variability obtained for all the instruments (as represented by the CV) was only 3.0 percent. The highest degree of variability was for between-test measurements obtained with the Kurz 541S. It was expected that measurements with the Kurz instruments would have a higher degree of variability since the response is related to the mass rate of air flowing through the orifice.

The purpose of conducting the different tests on separate days over a period of eight weeks was to obtain comparative measurements under different, naturally occurring, environmental conditions (pressure, temperature, humidity). The data representative of the environmental conditions during each test are shown on Table 2. As the data show, temperature, pressure and relative humidity varied over a range of 71.5 to 79° F, 733.7 to 756.2 mm Hg and 11 to 28 percent, respectively (not including conditions during retest of the Buck calibrator). The different environmental conditions resulted in the density of the air during the evaluation having a variation (as defined by the CV) of approximately 1.2 percent. Combining the variability associated with environmental conditions with that obtained with the constant volume devices, using the equation:

$$CV_k^2 = CV_{wtm}^2 + CV_{ec}^2$$

where CV_k = expected coefficient of variability to be associated with Kurz calibrators

CV_{wtm} = coefficient of variability associated with WTM calibration

CV_{ec} = coefficient of variability associated with environmental conditions

showed that the higher degree of variability obtained with the Kurz instruments cannot be totally attributed to the variation associated with environmental conditions. Also, why the same degree of variability was not obtained with both the Kurz meters is not known.

The comparison of the standard deviations determined for the between test calibrations for the respective devices using the "F" test showed that the degree of measurement variability was significantly different than that obtained with the WTM for all the devices except the Buck flowmeter. Using the "t" statistic and the average standard deviation for the intratest measurements, the number of measurements required to ensure that a calibration with the different instruments is within 0.1 L/min was calculated. This calculation showed that the WTM required one measurement, the Pocket Kurz and Buck required two and the Kurz 541S and Mast required three measurements to meet the requirement that the flow rate be within 0.1 L/min of the measured value.

CONCLUSIONS

None of the fast response flow measurement devices tested are as consistent in repeated measurements of the same flow rate as is the wet test meter. However, all of the devices are capable of being used to calibrate personal respirable dust sampling pumps to an accuracy of ±5 percent, with 95 percent confidence, if the appropriate number of multiple measurements are made and the devices are regularly calibrated against a volumetric flow standard. Calibration against a volumetric flow standard is particularly important because the response of some of the instruments (such as the Kurz) varies with air density. Instruments such as the Kurz need to be calibrated at an altitude near that at which they will be used.

The integrity of measurement made with these devices may not be as consistent as those obtained with the WTM. This was evident when some erroneous measurements were obtained with the Kurz Model 541S instrument and with the Buck Calibrator. Therefore, there should be some secondary check performed during the use of these instruments to insure they are operating properly.

4/ Tomb, Thomas F., and Treaftis, Harry N. Standard Calibration and Maintenance Procedures for Wet Test Meters and Coal Mine Respirable Dust Samplers, IR 1121, 1980.

5/ Reference to specific brands, equipment or trade names in this report is made to facilitate understanding and does not imply endorsement by the Mine Safety and Health Administration.

6/ Bernstein, D. M., R. T. Drew, and M. Lippmann. Calibration of Air Sampling Instruments, in Air Sampling Instruments for Evaluation of Atmospheric Contaminants, 6th edition, ed. by P. J. Lioy and M. J. Y. Lioy, Cincinnati, Ohio, (1983) p. K8.

7/ Perry, R. H., C. H. Chilton, and S. D. Kirkpatrick, ed. Chemical Engineers Handbook, 4th ed., McGraw - Hill, N. Y., (1963) pp. 5-9.

Table 1. - Average of Flow Rates Measured During Each Test
(30 Measurements Per Test)

Test	Orifice[1] Flow Rate L/min	Wet Test Meter Mean L/min	Wet Test Meter Standard Deviation(s) L/min	Mast Mean L/min	Mast Standard Deviation(s) L/min	Buck[2] Mean L/min	Buck[2] Standard Deviation(s) L/min	Kurz 541S Mean L/min	Kurz 541S Standard Deviation(s) L/min	Pocket Kurz Mean L/min	Pocket Kurz Standard Deviation(s) L/min
1	2.01	2.01	0.005	1.970	0.0651	1.964	0.0105	2.0	0.03	2.0	0.00
2	2.01	2.00	0.005	2.005	0.0298	1.976	0.0097	2.0	0.08	2.0	0.05
3	2.01	2.00	0.002	2.057	0.0461	1.993	0.0082	2.0	0.00	2.0	0.00
4	2.00	1.98	0.002	2.058	0.0625	1.980	0.0089	2.0	0.00	1.9	0.05
5	2.01	2.00	0.005	2.009	0.0376	1.971	0.0167	1.9	0.09	2.0	0.02
6	2.00	2.03	0.002	2.025	0.0179	1.990	0.0049	2.1	0.00	2.0	0.00
7	2.00	2.00	0.000	1.961	0.0272	1.931	0.0064	2.1	0.02	2.0	0.02
8	2.01	2.00	0.005	2.005	0.0253	1.943	0.0173	2.0	0.00	1.9	0.05
9	2.02	2.01	0.005	1.986	0.0279	1.974	0.0100	*[3]		2.0	0.04
10	2.01	2.01	0.000	2.010	0.0114	1.990	0.0069	2.0	0.05	2.0	0.05
Mean ($\bar{x}$)	2.01	2.00		2.009		1.971		2.0		2.0	
Standard Deviation (s)	0.014	0.013		0.0322		0.0204		0.06		0.04	
Coefficient of Variation	0.70	0.65		1.60		1.03		3.0		2.0	
Average of Standard Deviations			0.004		0.0390		0.0107		0.04		0.04

1/ Corrected to pressure, density and temperature conditions of Test 1.
2/ Measured at environmental conditions shown on Table 2.
3/ Invalid measurement.

Table 2. - Environmental Conditions (Barometric Pressure, Dry and Psychrometric Wet Bulb Temperatures and Moist Air Density and Relative Humidity) for Tests of Flow Measuring Devices

Test	P (mm Hg)	T_d (°F)	T_w (°F)	(g/l)	RH (%)
1	745.4	78.0	52.5	1.1578	11
2	737.2	75.5	55.0	1.1489	24
3	743.6	79.0	54.0	1.1524	14
4	736.0	72.0	52.0	1.1552	21
5	749.0	78.5	55.0	1.1614	18
6	752.0	71.5	53.5	1.1809	28
7	756.2	74.0	51.5	1.1832	15
8	741.5	79.0	56.0	1.1483	19
9	744.2	73.0	49.5	1.1671	11
10	733.7	75.0	55.0	1.1444	24

Environmental Conditions For Tests of the Buck Flow Calibrator

1	748.6	81.0	74.0	1.1467	72
2	750.2	77.0	61.0	1.1637	39
3	747.9	79.0	66.0	1.1538	50
4	743.2	79.0	67.5	1.1457	55
5	745.8	66.0	56.0	1.1814	53
6	736.5	80.0	65.0	1.1346	44
7	736.6	74.0	62.0	1.1480	50
8	744.8	72.0	60.0	1.1658	49
9	743.9	74.0	61.5	1.1597	48
10	746.8	68.0	57.0	1.1784	50

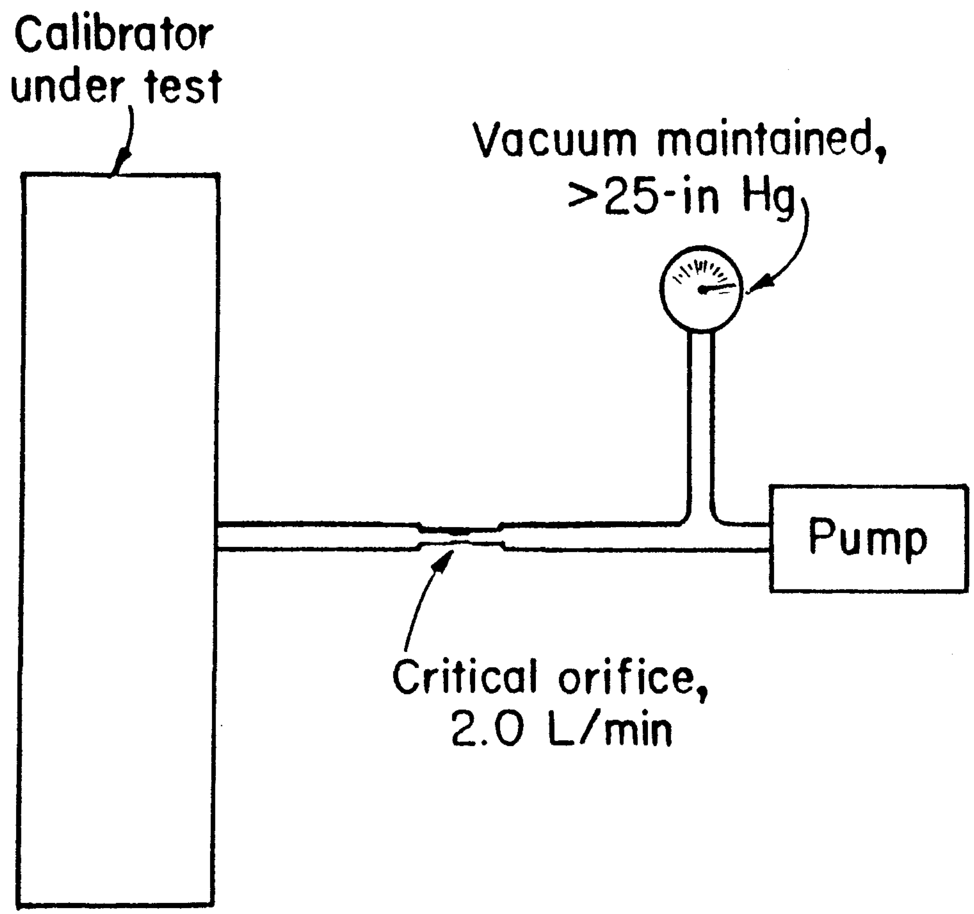

Figure 1. - Schematic - Experimental Setup