Instrument Requirements and Methods for Measuring Vacuum in Milking Machines

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Abstract. *The instrument specifications given in current international (ISO) and national (ASAE) standards state that measured values should be within 90% of the true amplitude of vacuum change at the various locations in the milking machine. Recommendations are given for the minimum sampling rate and response rate of instruments used to measure vacuum changes for dry, wet, milking–time, and cleaning–time tests. These minimum performance requirements should ensure that the measurement accuracy stated in the ISO and ASAE standards are met.*

A simple method was developed to measure the response rate of a vacuum recording system. The method can be used, quickly and easily, by field or laboratory technicians to specify the response rate of their vacuum recording systems. The predominant effects on response rate of vacuum recording systems are caused by the fittings connecting the electronic vacuum recorder to the measurement point. A major source of measurement error was water or milk in connecting tubes and fittings.

Dry and wet tests in the milkline and receiver confirmed previous studies showing that the rate of vacuum change during dry tests or in dry parts of the milking machine are much lower than those in wet parts of the machine. The fastest vacuum changes were measured in the short milk tube and mouthpiece chamber during a liner slip in a milking–time test. Measurements made in the short milk tube during wet tests corresponded well with those made during wet tests at the teat–end of the ISO standard udder.

Keywords. *Milking machines, Test instruments, Test methods.*

Tests of milking machine performance specified by the American Society of Agricultural Engineers (ASAE S518; 1996) and the International Standards Organization (ISO 5707; 1996) are based on measurements of vacuum changes over time made in the receiver, pulsator airline, milkline, and pulsation chamber. Some of these are done as dry tests with only air flowing in the milking machine and others as milking–time tests with air and milk flowing in the machine (IDF, 1999). Annex A of ISO 6690 (1996) and ASAE EP445 (1996) also describe a laboratory test of vacuum in the milking unit using a test point at the end of an artificial teat. This laboratory test is performed as a wet test with water supplied by an artificial udder flowing through the milking unit. The National Mastitis Council publication "Procedures for Evaluating Vacuum Levels and Air Flow in Milking Systems" (NMC, 1996) specifies an additional test for vacuum stability in the claw during milking.

ASAE EP 445 (1996) specifies that for milking–time and dry tests of vacuum stability in the receiver and milkline: "vacuum recorders shall be able to indicate vacuum levels with an accuracy of +/– 1.5 kPa and vacuum changes with an accuracy of +/– 0.5 kPa." ISO 6690 (1996) specifies that recording instruments used for wet tests of vacuum stability at the teat end must have less than 10% error in measuring vacuum difference (maximum – minimum within one pulsation cycle) and that the frequency response of the recorder must be greater than 500 Hz and filtered to less than 1000 Hz. This reference to frequency response is unclear, as no method is given to measure the frequency response of a vacuum recording system. Further recommendations are that the internal volume of connections to the measuring equipment should be kept to a minimum to avoid damping vacuum fluctuations. However, no details are given as to how to determine if the connections will meet the accuracy requirement. NMC (1996) specifies that the vacuum recording system used for milking–time tests in the receiver, milkline, and claw must be capable of measuring at least 90% of the true change in vacuum, without further description of the characteristics of such an instrument.

The instrument requirements for the tests prescribed by these international and national standards and guidelines are in need of clarification and further specification. In addition to the tests prescribed by these standards, attempts are being made in several countries to conduct milking–time tests at locations closer to the cow, at the teat end or in the short milk tube. The demands of testing in the short milk tube during

Article was submitted for review in June 1998; approved for publication by the Information & Electrical Technologies Division of ASAE in March 2001. Presented at the 1996 ASAE Annual Meeting as Paper No. 96–3018 and at the 1997 ASAE Annual Meeting as Paper No. 97–3038.

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milking are much higher than for the tests in the receiver and milkline.

Tan and Reinemann (1996) studied frequency characteristics of vacuum fluctuations in the dry parts of the milking machine to better understand and optimize vacuum regulation. The objectives of the study presented here are to extend this previous work by characterizing vacuum changes in the milking machine and unit during wet and milking–time tests, and to develop recommendations for test methods and test equipment for reliable measurement of vacuum changes in milking machines.

MATERIALS AND METHODS

A vacuum recording system is made up of an electronic vacuum recorder in combination with various tubes and fittings connecting the recorder to the milking machine. Most vacuum recorders used to test milking machine performance are digital devices that sample vacuum levels at some fixed rate. Various algorithms are used to analyze and report these data. Commercial vacuum recorders contain algorithms to automatically calculate the duration of the a–phase of pulsation (ISO 6690, 1996; ASAE EP445, 1996). This feature provides an easy method for measuring the response rate of a vacuum recording system.

Analog signals can be described in both the time and frequency domain. Fourier analysis can be applied to data to describe the waveforms using a combination of sinusoidal components of different frequencies. Likewise, data can be described in the time domain using parameters such as the period of repetitive signals or the rise time of wave fronts. The rise time used in this article is defined as the time for the signal to traverse from 10% to 90% of the excursion from a relative minimum to a relative maximum. Milking machine pulsation characteristics are described using both time and frequency parameters. Pulsation rate is described in the frequency domain as a number of cycles per minute. The a and c phases of pulsation are described in the time domain in a manner similar to a rise time. ASAE EP445 (1996) and ISO 6690 (1996) define the a–phase as the time for the vacuum to increase from +4 kPa to 4 kPa below the maximum pulsation chamber vacuum (typically about 40 kPa).

Direct connection to a fast–action electronic pulsator will produce a square wave with rise time of about 4 ms. Eliminating the volume of the long pulse tube, short pulse tube, and pulsation chamber produces a rise time, or a–phase, that is much faster than that produced during a pulsation test. A series of response tests was performed with commercial vacuum recording systems connected directly to an electronic pulsator using connection fittings commonly used in the field. The response rate of the vacuum recording system was taken as the change in vacuum during the a–phase (system vacuum – 8 kPa) divided by the duration of the a–phase.

REFERENCE RECORDING SYSTEM

A reference measurement system was assembled using a computer–based data acquisition board (DAS20, Keithley Instruments, Cleveland, Ohio) interfaced with pressure transducers (Px139 – 015D4V, Omega Engineering, Stamford, Conn.). The pressure transducers were specified by the supplier as having a response time of less than 1 ms. The limits of the reference system were tested as follows. A surgical glove was stretched over one end of a 16 mm (5/8 in) stainless steel tee. The other end of the tee was connected to a milking machine at 45 kPa vacuum. The vacuum sensor was connected to the third leg of the tee. The glove was then pierced with a needle while the computer–based data acquisition system recorded vacuum with a sample rate of 100,000 Hz and filtered to 10,000 Hz using a Blackman low–pass filter (Viewdac, 1991). This method produced a large rapid drop in vacuum with an amplitude of 27 kPa and fall time of 0.42 ms, followed by smaller cyclic fluctuations with an amplitude of 2.2 kPa and rise time of 0.20 ms. These vacuum changes are similar in form but much faster than those normally occurring in a milking machine. The rate of change of the large vacuum drop was 64,000 kPa/s. The “fluttering” that occurred after the large vacuum drop had a rate of change of 11,000 kPa/s and a fundamental frequency of about 1500 Hz. The reference system was thus shown to be capable of measuring vacuum changes up to 64,000 kPa/s and 1500 Hz.

CONNECTIONS TO THE SHORT MILK TUBE

The following fittings were used to connect the reference vacuum recorder to the short milk tube: 12, 14, and 16 gauge needles and blunt–end metal tubes with 2 mm and 3 mm internal diameters. The needles were inserted so that they protruded into the flow stream with their bevel ends facing both toward and away from the direction of the flow stream. One of the 2 mm metal tubes was fitted so that the end of the tube was flush with the internal surface of the short milk tube. Another was fitted so that it protruded into the flow stream. Tubing of various lengths connected these fittings to the vacuum transducers.

A single teatcup was connected to one teat of the type of flow simulator specified for wet tests in ISO 6690 (1996). The short milk tube was connected directly to a 73 mm milkline with a 16 mm diameter milk hose. Water, at room temperature, was used as the test liquid with flow rates of 1.0 and 2.0 L/min per teatcup. Air was admitted to the artificial teat at a flow rate of 150 L/min, as the liner opened, for two consecutive pulsation cycles to simulate a severe liner slip. Vacuum data was sampled at 500 Hz. The average and range (maximum – minimum) of vacuum during one pulsation cycle were measured in the short milk tube (Rasmussen et al., 1996).

DRY, WET, AND CLEANING–TIME TESTS IN THE MILKLINE AND RECEIVER

Dry tests, wet tests, and cleaning–time tests were performed to determine minimum rise times and maximum rates of vacuum change in the milkline and receiver during transient air admission. The reference vacuum recording system was connected to the measurement location with a 0.1 m tube (19,000 kPa/s response rate), and the vacuum data was sampled at 3000 Hz. Vacuum was measured at two locations in the milkline and one location in the receiver. The looped milkline had an internal diameter of 73 mm and total length of 23 m. Air was admitted by opening one teatcup of a milking unit, opening all four teatcups of one milking unit, or by removing one milk hose from its inlet. This range of air admission covered the typical range encountered in milking machine operation. No liquid was present in the system for the dry tests. Water was added to the milkline through artificial udders and milking units for the wet tests. Water was added to the milkline through a CIP manifold, and air was admitted through a commercial air injector for the cleaning–time tests.

Wet and Milking–Time Tests in the Milking Unit

Milking–time tests were performed in the University of Wisconsin milking parlor with the objective of creating worst–case conditions for high milk flow rate and to increase the likelihood of a naturally occurring liner slip. A series of wet tests were also performed with an ISO udder in the milking parlor. A low–level milkline and a 16 mm diameter long milk tube were used for all of these wet and milking–time tests. Two different claws were used: one with a 300 ml volume claw and 11 mm diameter short milk tube, and another with a 140 ml volume and 8 mm short milk tube. These wet and milking–time tests were performed with both simultaneous and alternate pulsation. One series of milking time tests was performed with a 500 g weight attached to the 300 ml claw to promote liner slips. Vacuum data was sampled at 3000 Hz in the short milk tube, short pulse tube, and mouthpiece chamber on the right front teatcup, and in the claw body. The connections to the vacuum recording system were made with 2 mm internal diameter fittings (65,000 kPa/s response rate) that were flush with the inner surface of the milking unit tubes. The data were stored and processed later to simulate a lower sample rate using a subset of the data.

Vacuum fluctuations in all of these tests were characterized in the frequency domain by applying the Fast Fourier Transform (FFT) function from Viewdac software (Viewdac, 1991) to the digitally sampled data. The maximum frequency component was taken as the highest frequency component with less than 10 dB reduction from the fundamental. Vacuum fluctuations were also characterized in the time domain by calculating the minimum rise or fall time of vacuum changes greater than 0.5 kPa. The maximum rate of change of vacuum was calculated as the change in vacuum divided by the rise or fall time over which it occurred, consistent with the method for quantifying the response rate of the recording systems.

Response Rate and Measurement Error

Wet tests were performed using an ISO standard udder to determine the effect of response rate on the error in measuring vacuum range in the claw and short milk tube. Four stainless steel tubes (2 mm inner diameter, 30 mm long) were connected around the circumference of one short milk tube of the milking unit. The ends of these tubes were mounted flush with the internal wall of the short milk tube. These connection fittings were connected to vacuum transducers with flexible tubes with 2 mm inner diameter and lengths of 0.1 m, 0.4 m, 1 m, and 2 m. The response rate of the connection systems used for these tests was 1900 kPa/s for the 2 m tube, 3900 kPa/s for the 1 m tube, and 5500 kPa/s for the 0.4 m tube, and 19,000 kPa/s for the 0.1 m tube. Another series of simultaneous measurements in the claw was done using 2 m connecting tubes and a 16–gauge needle (250 kPa/s), a 14–gauge needle (600 kPa/s), a 12–gauge needle (790 kPa/s), and a fitting tapped into the claw body (1200 kPa/s). The vacuum data were sampled at 2000 Hz. The vacuum range was calculated once per second (once for each pulsation cycle). Measurement errors were calculated relative to the reference system with 0.1 m tube connection (19,000 kPa/s).

Results and Discussion

Response Rate of Vacuum Recording Systems

The response rates of various vacuum recording systems using the method described above are shown in table 1. The fastest response rate measured with the reference system connected to an electronic pulsator was 6500 kPa/s. The limits of the reference system were thus well above the maximum rate of change produced by an electronic pulsator. There was no significant effect of vacuum level on the response rate over the range from 30 to 50 kPa. As expected, increased internal volume of connection fittings (longer and large diameter tubes and moisture traps) and restrictions to airflow (needles) reduced response rate. Although a small change in response rate was measured when tube diameter was decreased with recorder B, recorder A likely had insufficient time–resolution (1 ms) to indicate any difference. The connection fitting of recorder B, originally designed to hold a fiber filter, had an internal volume of approximately 10 cc. Inserting a smaller diameter tube into the fitting to reduce the internal volume increased response rate.

Table 1. Response rate of vacuum recording systems.

Recorder	Internal Diameter of Tube (mm)	Tube Length (m)	Fitting	Response Rate (kPa/s)
Reference System	3	0.1	Tee	>6500
Recorder A	3	0.1	Tee	>6500
	3	1	Tee	3900
	2	1	Tee	3900
	3	2	Tee	1900
	3	2	Trap, Tee	650
	3	2	12–gauge needle	790
	3	2	Trap, 12–gauge needle	460
	3	2	14–gauge needle	600
	3	2	Trap, 14–gauge needle	200
	3	2	16–gauge needle	250
	3	2	Trap, 16–gauge needle	140
Recorder B	3	0.1	Standard connection, Tee	4160
	2	1	Reduced volume connection, Tee	3750
	3	1	Reduced volume connection, Tee	3500
	2	1	Standard connection, Tee	3000
	3	2	Reduced volume connection, Tee	2300
	3	2	Standard connection, Tee	1700

CONNECTIONS TO THE SHORT MILK TUBE

The results of vacuum measured in the short milk tube during wet tests with various connection fittings are shown in table 2. The average of all measurements made with the reference system with 2 L/min of water flow were 45.8 kPa for average vacuum, 6.78 kPa for vacuum range, and 264 kPa/s for rate of change. When 150 L/min of air was admitted, simulating a liner slip, the average vacuum was 44.0 kPa, the vacuum range was 33.6 kPa, and the rate of vacuum change was 1120 kPa/s.

The agreement in average vacuum was within 1% (0.5 kPa) of the reference system during normal milking and within 2% (0.9 kPa) of the reference systems during a liner slip for all connection fittings. Considerable error was introduced when measuring both the vacuum range and maximum rate of change for all fittings that protruded into the flow stream. This was probably due to impact of water on the needle tip. Additionally, protruding connections may also produce measurement error by reducing the cross–sectional area of the tube and increasing the flow velocity. Both of these effects are more pronounced in the short milk tube than in the claw, milkline, or receiver because of its relatively narrow diameter and high flow velocities compared to these other measurement locations.

COMPARISON OF MEASUREMENTS MADE AT THE TEAT END, SHORT MILK TUBE, AND CLAW

A comparison of vacuum measured at the teat–end of the ISO udder and the short milk tube during wet tests is presented in table 3. The agreement between measurements at these two locations was very good with the average differing by less than 0.2 kPa (0.4%) and the range differing by less than 0.6 kPa (4.5%) for all conditions.

Table 4 presents a comparison of vacuum measured in the claw and in the short milk tube for milking–time tests. The 1 s average vacuum measured in the claw differed by less than 0.2 kPa (0.3%) from the 1 s average measured in the short milk tube during milking with the larger volume claw. The 1 s vacuum range measured in the claw differed by less than 0.9 kPa (10%) from the 1 s range measured in the short milk tube. Larger differences were found with the smaller volume claw with smaller diameter short milk tubes, with up to 1.4 kPa (3.5%) difference in the 1 s mean vacuum and 6.7 kPa (67%) difference in the 1 s range. Similar results were found when performing wet tests using an ISO udder.

Table 2. Reference system compared with a variety of connection fittings. Measurements made in the short milk tube using a single ISO teat with 2 L/min water flow (no slip) and with 2 L/min water flow and 150 L/min transient air admission (slip).

Connection Fitting	Tube Length (m)	Average Vacuum (% of reference)		Vacuum Range (% of reference)		Max Rate of Change (% of reference)	
		No Slip	Slip	No Slip	Slip	No Slip	Slip
2 mm ID tube, flush (reference)	0.1	100	100	100	100	100	100
2 mm ID tube, protruding	0.1	100	102	77	79	93	96
2 mm ID tube, flush	0.1 (water in tube)	100	101	45	100	73	104
12 gauge needle, bevel up	0.1	100	100	252	74	216	75
12 gauge needle, bevel down	0.1	100	102	93	64	66	65
14 gauge needle, bevel up	0.1	99	100	63	78	65	86
14 gauge needle, bevel down	0.1	101	102	139	81	96	80
16 gauge needle, bevel up	0.1	99	100	34	74	48	81
16 gauge needle bevel down	0.1	101	102	72	74	86	105

Table 3. Comparison of vacuum measurements in the short milk tube and ISO teat–end during wet tests.

Claw Volume (ml)	Pulsation Type	Average Vacuum (kPa)			Vacuum Range (kPa)		
		Mean of Difference	SD of Difference	R^2	Mean of Difference	SD of Difference	R^2
300	Alternate	0.08	0.06	1.00	0.30	0.30	0.99
300	Simultaneous	0.09	0.03	1.00	0.33	0.26	0.99
140	Alternate	0.18	0.12	1.00	0.43	0.34	0.96
140	Simultaneous	0.15	0.10	0.99	0.60	0.51	0.99

Table 4. Comparison of vacuum measurementsin the claw and short milk tube during milking–time tests.

Claw Volume (ml)	Pulsation Type	Flow Rate (L/min)	Average Vacuum (kPa)			Vacuum Range (kPa)		
			Mean Difference	Std. Dev.	R^2	Mean Difference	Std. Dev.	R^2
300	Alternate	2.3 – 4.5	0.18	0.08	0.99	0.59	0.66	0.49
300	Alternate	0.8 – 4.5	0.15	0.09	0.99	0.87	1.02	0.58
300	Simultaneous	1.3 – 5.6	0.18	0.12	0.97	0.33	0.41	0.98
300	Simultaneous	1.6 – 2.8	0.17	0.02	1.00	0.12	0.31	0.98
140	Alternate	2.1 – 5.0	0.14	0.15	0.94	2.17	11.14	0.22
140	Simultaneous	1.8 – 3.1	1.43	0.62	0.38	6.69	11.91	0.42
140	Simultaneous	2.6 – 5.0	1.34	0.78	0.94	6.74	11.91	0.98
140	Simultaneous	1.6 – 2.8	0.41	0.38	0.00	0.35	2.07	0.01

Table 5. Characteristics of vacuum changes in the milking machine and milking unit and recommended minimum sample rates.

Test Type	Test Location	Event	Minimum Rise or Fall Time (ms)	Maximum Rate of Change (kPa/s)	Maximum Frequency Component (Hz)	Sample Rate from Fourier (Hz)	Sample Rate from Rise Time (Hz)
Dry	Receiver	Milk hose removed	90	26	4	**24**	22
	Milkline	Milk hose removed	20	90	4	24	**100**
Wet	Receiver	Milk hose removed	100	25	4	**24**	20
	Milkline	Milk hose removed	51	260	8	**48**	39
	Short milk tube or ISO teat–end	High flow rate	8.5	700	22	132	**240**
Milking–time	Claw	High flow rate	32	220	5	30	**63**
		Liner slip	8.0	640	16	96	**250**
		Squawk	1.9	2200	280	**1700**	1100
	Short milk tube	High flow rate	12	700	13	78	**170**
		Liner slip	1.9	6300	62	370	**1050**
		Squawk	1.2	12,000	420	**2500**	1700
	Mouthpiece chamber	High flow rate	138	210	3	**18**	14
		Liner slip	8.0	800	4	24	**250**
		Squawk	1.2	15,000	210	1300	**1700**
Cleaning–time	Milkline	Cleaning slug	18	2000	7	42	**110**

Dry, Wet, Milking, and Cleaning–time Tests

The characteristics of vacuum changes for dry, wet, milking, and cleaning–time tests at various measurement locations are given in table 5. The minimum rise time and maximum rate of change for vacuum changes greater than 0.5 kPa are reported. The maximum frequency component was determined using the FFT method described above.

A recording of the vacuum in the short milk tube during milking with a milk flow rate of about 7 kg/min is shown in figure 1. This milk flow rate is greater than that for 95% of high–producing Holstein cows in the U.S. and France (Stewart et al., 1993; Billon and Blanchard, 1993) and hence is representative of a high milk flow rate. Several distinct frequency ranges are apparent in this recording. The first 150 ms is representative of normal milking. A fall time (t_{f1} = 16 ms) typical of normal milking conditions in the short milk tube is shown in the figure to illustrate the method. The rapid vacuum drop beginning at about 160 ms is a result of air admitted to the liner at the initiation of a liner slip. A typical fall time for a liner slip is also shown on the figure (t_{f2} = 1.9 ms). This liner slip is followed by periodic high–frequency vacuum fluctuation (from 320 to 400 ms) associated with intermittent air admission at the mouthpiece produced by the opening and closing of the seal between the liner and mouthpiece. This frequency is in the audible range and accounts for the characteristic sound referred to as an audible liner squawk. The amplitude of this high–frequency component was greatest in the mouthpiece chamber and short milk tube and occurred at lower levels in the claw and pulsation chamber. The sample rate indicated in figure 1 by the dots on the vacuum signal is sufficient to capture the detail of the vacuum changes occurring during normal milking. However, it is clearly insufficient to accurately describe the vacuum changes occurring during a liner slip or liner squawk.

Sampling theory suggests that if a continuous signal is sampled (f_{sample}) at twice its highest–frequency component

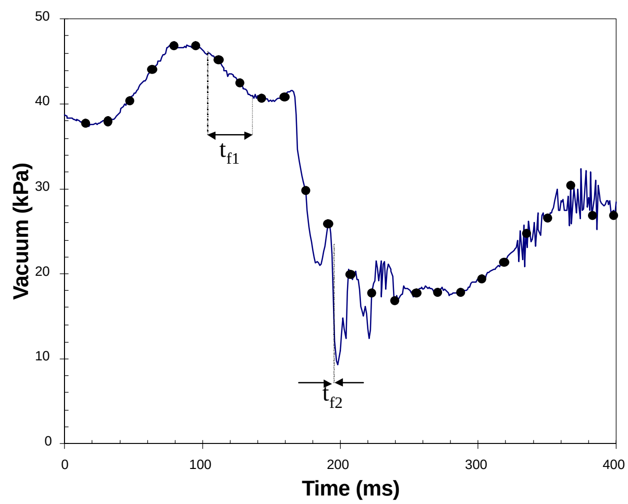

Figure 1. Example of a liner slip measured in the short milk tube.

(f_{max}), then there will be no loss of information if the sampled signal is reconstructed using an ideal low–pass filter with cutoff frequency: $f_{max} < f_{cutoff} < f_{sample} - f_{max}$ (Rugh, 2000). This places the cutoff frequency at the maximum frequency component and requires foreknowledge of this frequency. If the cutoff frequency is chosen poorly, then the reconstructed signal will not resemble the original. Practical recommendations for digital sampling devices are therefore 5 to 6 times the highest frequency component of the signal (Reissland, 1989; Gregory, 1996). The minimum sample frequencies determined from Fourier analysis given in table 5 are 6 times the maximum frequency component.

Minimum sample rates determined using a time domain approach are also presented in table 5. The maximum sampling interval is taken as ½ of the rise time. This method will result in three measurement points on the rising or falling face of the fastest vacuum change. These time and frequency methods to specify a minimum sample rate are approximately equivalent for sinusoidal waveforms, as the rise time of a sine wave is about 1/3 of the total period:

$$[\sin^{-1}(0.8) - \sin^{-1}(-0.8)] / 2\pi = 0.295 \quad (1)$$

The minimum sample rates from frequency domain and time domain methods are comparable for many of the measurement situations given in table 5. However, the Fourier method gives a significantly lower sample rate for rapid, non–repetitive vacuum drops such as occur during a liner slip. It is important to accurately characterize these rapid vacuum drops, as they are believed to be the source of reverse pressure gradients in the milking unit. Using the higher sample rate derived from these two methods (**bold** in table 5) will ensure that regular as well as irregular vacuum fluctuations are measured correctly.

Response Rate and Measurement Error

The effect of the response rate of the recording system on the error in measuring vacuum range in the short milk tube and claw is illustrated in figure 2. The vacuum range for these tests averaged 9.5 kPa. A 10% error therefore corresponds to about 1 kPa. The maximum rate of change is about 220 kPa/s in the claw and about 700 kPa/s in the short milk tube. These results suggest that the error in measurement of the vacuum range will be less than 10% when the response rate of the recording system is 2.5 times the fastest rate of change of the signal in the claw and 3.5 times the fastest rate of change in the short milk tube. For measurement error less than 0.5 kPa or 5%, the ratio of the response rate to the fastest rate of change must be increased to 3.5 in the claw and to 5 in the short milk tube.

It was clear during these experiments that as the length of tubes or the volume of connection fittings increased, the amount of liquid drawn into the measurement system increased, and that liquid in the connecting tubes was a major source of measurement error. This effect may have reduced the actual response rate of the recording system for connections to the short milk tube. Measurements at wet locations should be done using the shortest possible connecting tubes to avoid drawing water into the measurement system, and the connection fittings should be cleared of liquid immediately before taking measurements.

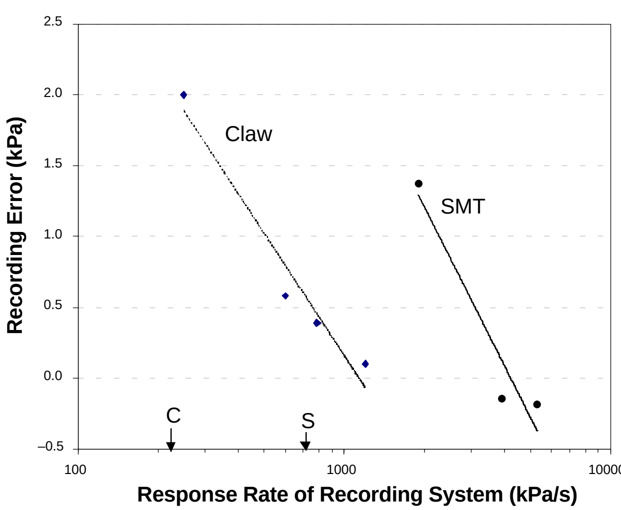

Figure 2. Effect of response rate on the error in measuring vacuum range in the claw and short milk tube (SMT). The maximum rate of vacuum change in the claw (C) and short milk tube (S) are also noted on the x–axis of the graph.

Conclusions

The agreement between measurement of average vacuum and vacuum range in the short milk tube and at the teat–end of the ISO udder during a wet test was good. The agreement between average vacuum measured in the claw and short milk tube was good for all test conditions. The agreement between vacuum range measured in the claw and short milk tube was good for a large–volume milking unit, but considerable difference was noted for a small volume unit.

Measurement in the claw will give a good indication of average milking vacuum for all types of milking units, and a good indication of vacuum range (fluctuation) for milking units with short milk tube diameter greater than about 10 mm. Because the claw is easy to access, it is the recommended test location for routine field investigations when average milking vacuum is of primary interest. For research studies on cause and effect relationships between vacuum fluctuation and milking performance or for field tests of vacuum stability during milking, measurements should be made in the short milk tube, especially for milking units with short milk tubes less than 10 mm in diameter.

A simple method has been developed to measure the response rate of vacuum recording systems. The predominant effect on response rate of electronic vacuum recorders tested was due to the fittings used to connect to the measurement point. The presence of water or milk in connecting tubes and fittings also produced considerable measurement error. The internal volume of the measurement system should be minimized to prevent water or milk being drawn into the measurement fittings. The inner diameter of connections and the way that they are mounted on the milking machine should be such that the connection fittings and tubes allow liquid to drain freely. Efforts should also be made to clear the connecting tubes and fittings of liquid immediately before taking measurements. Measurements made in the short milk tube should be made with fittings that are flush with the internal surface and as close as possible to the liner end of the short milk tube.

The response rate required to accurately measure vacuum changes in the milkline and receiver and normal milking conditions in the claw can be accomplished with commercial vacuum recorders and long connecting tubes, provided that the response rate of the recording system is sufficient and great care is taken to clear connecting tubes and fittings of water or milk immediately before wet and milking–time tests. Accurate measurement of vacuum change in the short milk tube during normal milking can be accomplished only if care is used to select connection fittings to achieve the required response rate of the recording system. Accurate measurement of vacuum change during liner slip or liner squawk can only be accomplished with the vacuum sensor located very near the measurement point.

The results of this study can be used to recommend requirements of vacuum recording systems for tests of average vacuum and vacuum range specified by ISO, ASAE, and NMC, as well as measurements made in the short milk tube during milking. Higher accuracy may be required for special purposes.

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