HYSTERESIS OF THE DAIRY COW'S TEAT AS AFFECTED BY VACUUM LEVEL RATES OF CHANGE

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Teat end hysteresis, based on teat end expansion and contraction due to the application and release of vacuum, was investigated for three rates of change of vacuum level. These three rates correspond to slow, medium, and fast teat cup liner wall movement. Hysteresis ratio increased significantly ($P \leq 0.01$) at faster rates. Teat end tissue returned about 35–40% of the energy input to the teat at the slow rate as compared to about 15–20% at the fast rate. Results suggest that rapid changes in vacuum level and fast liner wall movement should be avoided.

INTRODUCTION

Millions of dairy cows are milked twice a day with mechanical milking machines. The basic principle in machine milking, which has been in use for over 80 yr, involves the application of a reduced pressure (a vacuum level of 35–50 kPa below atmospheric pressure) below and around the teat inside a flexible rubber liner.

Use of milking machines has been widely and increasingly adopted. Several attempts have been made to improve and modify the commonly used basic system for more efficient and safer removal of milk. Yet, despite extensive research, teat responses to dynamic pressures applied in the milking process remain insufficiently understood and applied to equipment design and operating criteria. The dairy cow's teat and its physiological responses, in terms of teat end diameter and milk flow rate, to step and sinusoidal changes in vacuum level have been investigated (Reitsma 1977). Machine parameters, such as vacuum level and fluctuations, pulsation rate and ratio, and liner design, have been studied relative to milk removal efficiency and their possible relationship to mastitis (e.g., Kingwill et al. (1979)).

Expansion and contraction of the teat end upon application and release of a vacuum level do not follow identical paths of response (Gupta 1984). Hysteresis is defined as the failure of a system to follow identical paths of response upon application and withdrawal of a forcing agent (Fedullo et al. 1980). Because hysteresis represents the capability of the teat to dissipate energy, it will affect streak canal opening and closing. This may therefore affect milk flow rate and also bacterial entry. The latter may consequently affect the incidence of mastitis. Mastitis is commonly considered to be the most serious disease and economic problem on dairy farms.

OBJECTIVES

The main objective of this research was to determine hysteresis present in the dairy cow's teat, based on teat end expansion and contraction, when applying three rates of step changes in vacuum level uniformly to the outside of the teat during milk removal. Specific objectives were:

(1) To plot both step input vacuum level changes and teat end diameter changes in parallel as a function of time.

(2) To compute both teat response and applied vacuum level variables.

(3) To plot hysteresis curves for the three rates of change of vacuum level as a function of the pressure differential across the teat canal and to compute the hysteresis ratio (defined as the area between the loading curve (vacuum application resulting in teat end expansion) and unloading curve (vacuum release resulting in teat end contraction) as a percentage of the area below the loading curve (Gupta and Reitsma 1984)).

(4) To compare the hysteresis ratio for three rates of change of vacuum level between front and rear teats.

REVIEW OF LITERATURE

The teat, a biological structure, makes direct contact with only one moving part of the milking machine—the liner (American Society of Agricultural Engineers ASAE 1984). Many biological systems have been investigated by applying control system theory and techniques (Milsum 1966). Both step and sinusoidal inputs are commonly used and application of these to teats provided a better insight into milk removal and teat deformation (Reitsma 1977). A step input to the teat can provide conceptual insight into teat response with the conventional two-chambered teat cup.

A study of hysteresis of the teat end provides information on its visco-elastic behavior. Few studies focus on elastic behavior of the teat. Teat ends behaved as a nonlinear elastic body and teat stiffness increased with increased loading (Townsend 1969). Radial stretching of the streak canal showed a visco-elastic behavior (Stettler 1973). Teat tissue behaved as an incompressible pseudo-elastic material during machine milking (Gates 1984).

Hysteresis is a characteristic of many biological materials and represents a visco-elastic response to loading and unloading. Factors such as tissue elasticity and stress relaxation help explain the phenomenon of hysteresis (e.g., Ruch and Patton (1965)). Change of shape had a greater effect on hysteresis loss of rubber than the level of stresses present (Holownia 1979). Streak canal closing continued further during the first 2 h after each milking (McDonald 1975) suggesting a visco-elastic behavior. A slower change of vacuum level in the pulsation chamber decreased hysteresis of liners (Reitsma and Breckman 1985). Hysteresis increased for liners requiring a larger pressure differential for closure (Uhmann and Thalheim 1980).

A review of literature on hysteresis of the dairy cow's teat indicated a lack of information in this area (Gupta 1984).

EXPERIMENTAL METHODS

A previous paper showed in detail most

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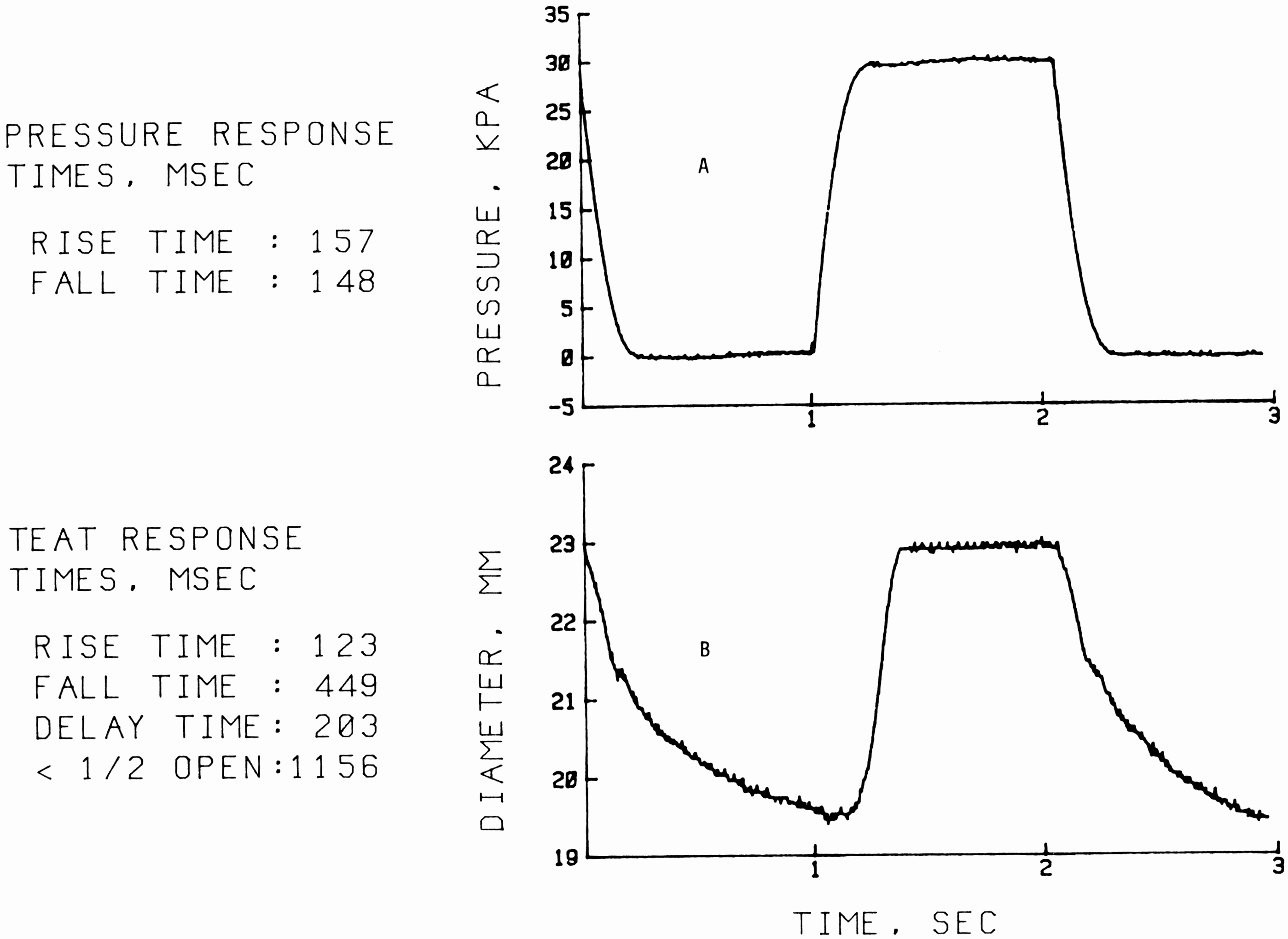

Figure 1. Typical plot of step input vacuum level change (A) around the teat and resulting teat end diameter response (B), both as a function of time for the right rear teat of a cow.

of the measurement and analysis techniques, including a description of the teat chamber, teat end diameter transducer and milking procedure (Gupta and Reitsma 1984). Next follows a description of the step vacuum level input to the teat, inserted into the teat chamber, for three rates of change of vacuum level and of the statistical design.

Step Vacuum Level Input

Alternate connection of the teat chamber to atmospheric pressure and a vacuum level of 30 kPa provides changes in vacuum level to the teat. A restrictor in the vacuum supply controls the rise time of vacuum level changes. A restrictor in the atmospheric pressure supply controls the fall time of vacuum level changes. Figure 1 shows a typical plot of step input vacuum level changes around the teat and resulting teat end diameter changes. The three rates of change of vacuum level applied (0−30 kPa; larger changes showed little or no additional teat end expansion (Reitsma and Scott 1979), in terms of three vacuum level rise and fall times, are: 50, 150 and 300 msec, respectively. The second value represents a typical average value for liner opening and closing times (Reitsma and Breckman 1985). The selected values of 50 and 300 msec represent a much faster and slower rate of vacuum level changes.

Statistical Design

Table I shows the layout of the statistical design of the experiment for applying three rates of vacuum level changes to a front and a rear teat of three cows over 3 days.

T1, T2, and T3 represent three rates of loading (vacuum application) and unloading (vacuum release) in terms of three vacuum level rise and fall times of 50, 150, and 300 msec, respectively.

The three cows were numbered randomly from 1 to 3. Each day, measurements were taken on one front teat and one rear teat of each cow. The cows were milked in the same sequence with a different treatment for each cow. Three

TABLE I. LAYOUT OF THE EXPERIMENTAL DESIGN FOR APPLYING THREE RATES OF VACUUM LEVEL CHANGES TO TEATS OF THREE COWS OVER 3 DAYS

Cow	Teat location†	Day 1	Day 2	Day 3
1	FR, RR	T1‡	T2	T3
2	FR, RR	T2	T3	T1
3	FR, RR	T3	T1	T2

†FR, front right teat; RR, rear right teat.
‡T1, T2 and T3 represent rise and fall times of 50, 150, and 300 msec, respectively.

treatments on three cows over 3 days made this experiment a Latin square design. However, the two teat locations of each cow made it a split-plot on this original Latin square design. An analysis of variance of all measured variables used the following model:

$$Y_{ijkl} = m + t_i + c_j + d_k + p_l + t{*}p_{il} + e_{ijkl}$$

where Y_{ijkl} = observation; m = mean; t_i = treatment effect; c_j = cow effect; d_k = day effect; p_l = teat location effect; $t{*}p_{il}$ = interaction treatment and teat location; i = 1, 2, 3 treatment number; j = 1, 2, 3 cow number; k = 1, 2, 3 day number; l = 1, 2 location (front, rear); and e_{ijkl} = error term.

RESULTS AND DISCUSSION

Table II lists the mean and standard error (SE) of the mean of each of the step input variables for the three rates of vacuum level changes.

The purpose of the above analysis was to verify uniformity of the applied step input variables for the three rates of vacuum level changes applied to the teats of the three cows over 3 days. The small SE of the mean for most of the variables verified uniform application to all the experimental units. Rise and fall times for the third treatment varied considerably more than for the first and second. In the first and second treatments the vacuum level reached its maximum quite rapidly and there was less chance of leakage between the teat and the mouthpiece of the teat chamber. For the third treatment, the vacuum level in the teat chamber did not reach atmospheric pressure for cow 1 on the third day while the maximum vacuum level was 29.9 kPa. This resulted in a smaller step change in vacuum level and in rise and fall times of 212 msec and 276 msec, respectively, contributing to a larger SE of the mean for rise and fall times. Other step input variables were quite consistent and varied little between cows from one day to the next. Gupta and Reitsma (1984) discussed in detail the variation in the step input variables.

Table III lists the teat response variables for front and rear teats separately. Each value in this table is the mean of the three cows, for the right front and rear teat separately, for each of the three treatments.

Table IV lists the results of the statistical analysis of the teat response variables. Because of the small size of this experiment, Table IV shows a third probability level of 10% besides the generally used 1% and 5% levels (Steel and Torrie 1980).

Vacuum level at half-way expansion (VHO) of the teat (during loading) differed close to significantly ($P \leqslant 0.10$) for treatment and teat location (Table IV). It was always higher for rear than front teats suggesting slower expansion which is also evident from the significantly ($P \leqslant 0.05$) longer rise time for rear teats. There was a decreasing trend of the vacuum level at half-way expansion with slower changes in vacuum level (Table III).

The factor treatment affected vacuum level at half-way contraction (VHC) of the teat (during unloading; Table IV). Slower rates of vacuum level changes increased the vacuum level at half-way contraction while they decreased the vacuum level at half way expansion. These two trends both contributed to less hysteresis at slower vacuum level rates of change.

The teat rise time (TRT) differed significantly ($P \leqslant 0.05$) for the factor location and was close to significant ($P \leqslant 0.10$) for cow. Front teats expanded in a shorter time than rear teats (Table III).

The foregoing suggests that the sphincter muscle and teat end tissue of rear teats resist expansion more than those of front teats. Teat ends required the longest time to respond at the slowest vacuum level rates of change.

The teat fall times (TFT) were much longer than the rise times. The teat fall time differed close to significantly ($P \leqslant 0.10$) for the factors of treatment, cow, and day (Table IV). It was the only variable to show a significant interaction

TABLE II. MEAN AND STANDARD ERROR (SE) OF THE MEAN OF SEVERAL STEP INPUT VARIABLES FOR THE THREE RATES OF VACUUM LEVEL CHANGES

Step input variable	Treatment	Mean	SE of the mean
Step input period (msec)	1, 2, 3	2062	0.62
Maximum vacuum level (kPa)	1, 2, 3	30.1	0.03
Minimum vacuum level (kPa)	1, 2, 3	0.1	0.18
Vacuum level rise time (msec)	1	55	0.97
	2	165	3.91
	3	282	14.11
Vacuum level fall time (msec)	1	54	0.70
	2	145	2.14
	3	345	15.62

TABLE III. MEANS OF TEAT RESPONSE VARIABLES FOR FRONT RIGHT (FR) AND REAR (RR) TEAT OF THREE COWS FOR EXPERIMENT RLOAD. THE TREATMENTS 1, 2, AND 3 REPRESENT THREE RATES OF CHANGE OF VACUUM LEVEL

			Teat response variable†														
Treatment	Teat location	n‡	VHO (kPa)	VHC (kPa)	TRT (msec)	TFT (msec)	TDT (msec)	TLT (msec)	TMT (msec)	ALD (mm)	ASD (mm)	TDR	DSP (mm)	ARL (kPa·mm)	ARU (kPa·mm)	HYS (kPa·mm)	HYR (%)
1	FR	3	28.2	0.7	59	349	141	1005	1059	21.9	18.4	1.19	3.4	98.9	18.3	80.7	81.0
(50 msec)	RR	3	29.8	−0.2	147	474	67	1021	1053	20.5	17.8	1.15	2.7	86.0	11.9	73.8	84.4
2	FR	3	27.0	4.0	115	534	121	1051	1018	22.0	18.9	1.16	3.1	89.3	22.9	65.8	73.8
(150 msec)	RR	3	28.1	2.4	141	457	151	1073	988	20.9	18.2	1.15	2.7	78.4	18.5	60.2	76.1
3	FR	3	20.0	6.2	149	498	117	905	1152	21.0	17.7	1.18	3.3	69.4	26.2	42.8	60.3
(300 msec)	RR	3	23.4	6.8	200	528	110	941	1128	20.5	17.7	1.16	2.8	61.9	21.0	41.0	65.1

†VHO, vacuum level at half-way expansion of the teat; VHC, vacuum level at half-way contraction of the teat; TRT, teat rise time; TFT, teat fall time; TDT, teat delay rise time; TLT, time teat less than half open; TMT, time teat more than half open; ALD, average largest diameter; ASD, average smallest diameter; TDR, teat end diameter ratio; DSP, step change in teat end diameter; ARL, area under loading curve (teat expansion); ARU, area under unloading curve (teat contraction); HYS, hysteresis; HYR, hysteresis ratio.
‡n, number of observations.

TABLE IV. RESULTS OF THE ANALYSIS OF VARIANCE FOR ALL MEASURED TEAT RESPONSE VARIABLES OF EXPERIMENT RLOAD

	Teat response variable†														
Source of variation	VHO	VHC	TRT	TFT	TDT	TLT	TMT	ALD	ASD	TDR	DSP	ARL	ARU	HYS	HYR
Treatment	c‡	c		c	s								s		S
Cow			c	c				s	s				s		s
Day				c											
Location	c		s					S			c		S		
Treatment × location				s											

†VHO, vacuum level at half-way expansion of the teat; VHC, vacuum level at half-way contraction of the teat; TRT, teat rise time; TFT, teat fall time; TDT, teat delay rise time; TLT, time teat less than half open; TMT, time teat more than half open; ALD, average largest diameter; ASD, average smallest diameter; TDR, teat end diameter ratio; DSP, step change in teat end diameter; ARL, area under loading curve (teat expansion); ARU, area under unloading curve (teat contraction); HYS, hysteresis; HYR, hysteresis ratio.
‡S, highly significant ($P \leqslant 0.01$); s, significant ($P \leqslant 0{,}05$); c, close to significant ($P \leqslant 0.10$).

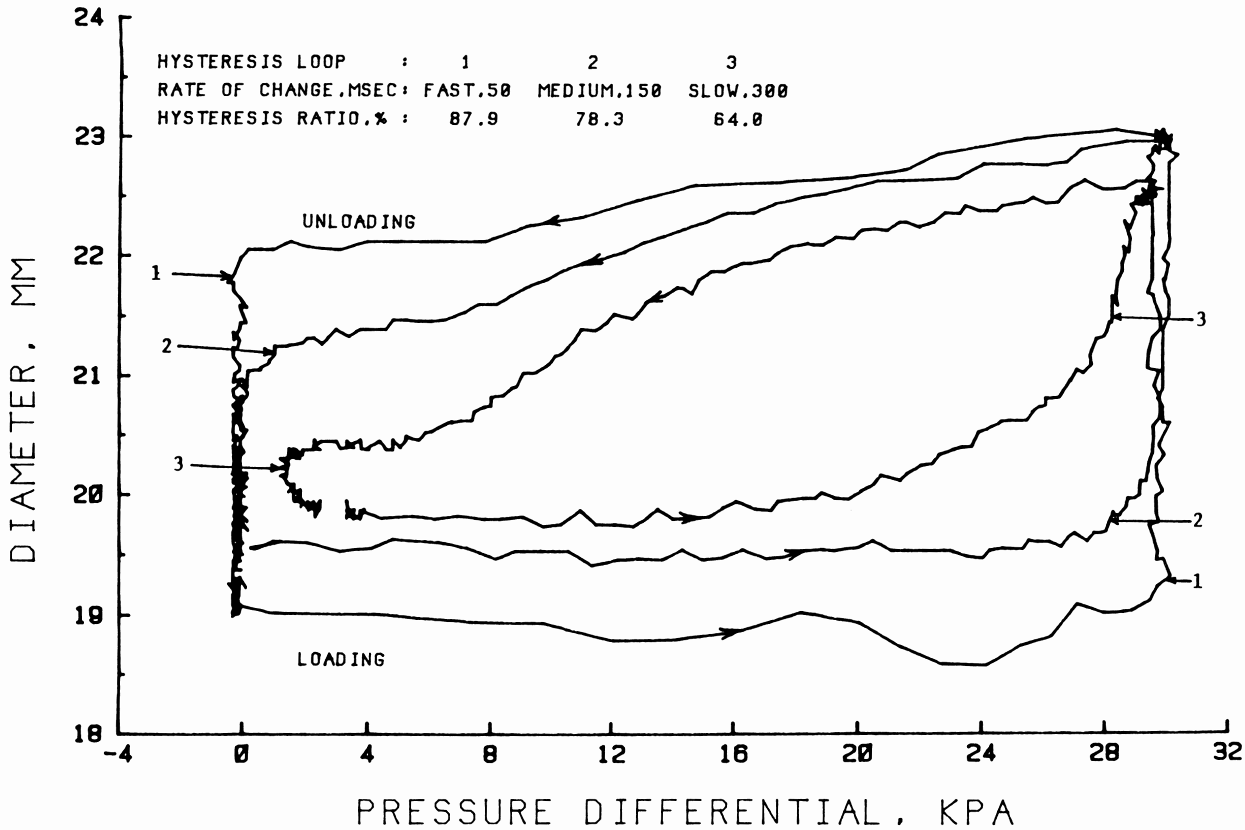

Figure 2. Hysteresis curves for a rear teat of a cow for three rates of change of vacuum level.

between treatment and teat location. This suggests that the factors are not independent of one another.

The teat delay rise time (TDT) was the longest for treatment 2 and differed significantly ($P \leq 0.05$) between treatments (Table IV).

Length of time when teats were less than half open time (TLT) and more than half open (TMT) showed no significant differences for all four factors and the interaction of treatment and location. This suggests that durations of milk and no-milk flow would not likely differ significantly either.

The dimensional changes of external teat end diameter were statistically analyzed based on four variables: (1) average smallest diameter (ASD), (2) average largest diameter (ALD), (3) step change in teat end diameter (DSP), and (4) teat end diameter ratio (TDR).

Both ASD and ALD differed significantly ($P \leq 0.05$) between cows and ALD was also highly significant ($P \leq 0.01$) for location. Larger expansion and tead end diameter ratio of front teats than rear teats agree with earlier findings (Reitsma 1977). The mean values of the external teat end diameter at atmospheric pressure (ASD) differed significantly ($P \leq 0.05$) between cows only. This suggests differences between cows, not other factors. A mean teat end diameter ratio (TDR: expanded/unexpanded teat end diameter) was calculated and used in the statistical analysis to account for small differences in transducer placement on the teat end, or to the pressure differences inside the teat cistern, or both, from day to day and cow to cow. This ratio did not differ among treatments, cows, days, or teat location (Table IV). The radial expansion of each teat (DSP: step change in teat end diameter) was nearly constant for each of the three treatments. It differed close to significantly ($P \leq 0.10$) between teat locations corresponding to the findings for the average largest diameter (ALD).

The four variables relating to hysteresis are: (1) area under the loading curve (ARL) during teat expansion; (2) area under the unloading curve (ARU) during teat contraction; (3) hysteresis (HYS), i.e., the area between ARL and ARU; and (4) hysteresis ratio (HYR), i.e., hysteresis as a percentage of the area below the loading curve (ARL).

The area under the loading curve did not show any significant differences for any of the factors (Table IV). It showed a decreasing trend for slower rates of change of vacuum level. The data also suggest a larger energy input to front than rear teats. This corresponds to faster expansion by the larger front teats than the rear teats.

The area under the unloading curve represents the energy returned by the teat. This was highly significant ($P \leq 0.01$) for location and significant ($P \leq 0.05$) for treatment and cow. The two areas, under the loading and unloading curves, showed a reversed trend for treatments and were consistent for teat location (Table III).

Hysteresis, i.e., the area between the loading and unloading curves, showed no significant differences for any of the factors, as did the area under the loading curve. Therefore, these two variables are least sensitive in detecting hysteresis-related differences.

The hysteresis ratio showed highly significant ($P \leq 0.01$) differences between treatments and was significant ($P \leq 0.05$) for cows. It was not significant for the factor location but rear teats always had a larger hysteresis ratio than front teats (Table III). For faster rates of vacuum level changes, more energy was input to the teat and smaller amounts returned resulting in a larger hysteresis ratio for faster rates of changes (Table III). Energy returned from the teat end was about 17%, 25% and 37% for treatments 1, 2, and 3, respectively. The hysteresis ratio decreased very significantly ($P \leq 0.01$) as the rate of vacuum level change decreased (Tables III and IV). The larger hysteresis ratio for rear than front teats suggests a stronger visco-elastic behavior of rear teats compared with front teats. Gupta and Reitsma (1984) reported a hysteresis ratio of 75% for rear teats compared with 69% for front teats.

Figure 2 shows three sets of hysteresis curves of the rear teat of a cow for the three rates of vacuum level change. It shows that, at a fast rate of vacuum level change, most of the teat expansion took place at the maximum vacuum level, whereas at the slow rate, expansion was more gradual. This reduced the area between the loading and unloading curves at the slow rate resulting in a lower hysteresis ratio.

The higher hysteresis ratios and the significantly smaller areas under the unloading curve for rear teats than front teats may help explain why inadequate pulsation results in more infections in rear than front quarters (Reitsma et al. 1981). This observation, coupled with increased hysteresis ratios at faster vacuum level changes, helps to provide a basis for avoiding fast liner wall movement and rapid vacuum level fluctuations.

CONCLUSIONS

The main conclusions from this study are:

(1) The rate of loading (teat end expansion during vacuum application) and unloading (teat end contraction during vacuum release), by applying step changes in vacuum level, affected very significantly ($P \leq 0.01$) the hysteresis ratio of the dairy cows' teat end. Hysteresis ratio was 83% for a fast rate of vacuum level change compared with 63% for a slow rate.

(2) About 35−40% of the energy input to the teat was recovered at a slow rate of vacuum level change.

(3) Only about 15−20% of the energy input to the teat was recovered at a fast rate of vacuum level change.

(4) The area under the unloading (teat end contraction) curve was very significantly ($P \leq 0.01$) larger for front than rear teats.

(6) Higher hysteresis ratios for rear than front teats may explain why more mastitis occurs in rear than front teats.

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