ABSTRACT
Air flow utilization was measured continuously for an hour during one milking in 31 commercial milking parlors. For analysis, recorded air flow was sampled at 5-s intervals for 30 min, and for each parlor a histogram and cumulative distribution curve were plotted of air usage versus frequency of that air usage. Normal air usage was far less than maximum usage most of the time, but the analysis was based on air consumption which included 99% of the air flows sampled. Factors significantly affecting air usage were number of units and number of cows milked per hour. Based on sampled air flows, the required air flow rate was predicted by a regression equation: air usage (liters/second) = 2.35 + .32(number of milking units) + .093(number of cows milked per hour).

To predict minimum pump capacity required to maintain stable line vacuum, air loss from leaks and minimum air flow through the regulator were considered. A second equation was derived for this case.

INTRODUCTION
Mastitis infections can cause a 5 to 25% loss in milk production (4) and as one of the most expensive diseases in dairying, research efforts have been substantial to reduce these infections. Although mastitis infection rates are higher during the dry period than during lactation (6, 14), the possible role of milking equipment has been investigated.

Nyhan (7) demonstrated a relationship between irregular vacuum fluctuations and increased infectivity. Thompson et al. (15) also demonstrated greater risk of mastitis infections under these conditions. Thiel et al. (12) confirmed Nyhan’s hypothesis that vacuum fluctuations could cause a mechanical transfer of bacteria into the teat sinus. Reverse pressure gradients during severe cyclic and irregular vacuum fluctuations may cause reverse jetting of milk droplets which could impinge upon the teat end with enough force to penetrate the streak canal (11).

Irregular vacuum fluctuations may be minimized by a more responsive regulator and adequate vacuum pump capacity. Fluctuations from milk lift may be dampened by shorter and larger diameter milk tubes with a continuous downward slope to avoid slugging (13). Cyclic vacuum fluctuations may be minimized by vented claws, larger bore short milk tubes, and alternate pulsation (5).

Emphasis in the US on reducing vacuum fluctuations has been directed toward vacuum pump capacity. The 3A Accepted Practices (16) recommend 2.8 liters/s for each milking unit plus capacity for a vacuum operated releaser, pulsed vacuum line, milk meters, sanitary couplings, inlets, and regulators. One liter/s is equal to 2.119 CFM (American Society of Mechanical Engineers). A sample calculation for a four-unit parlor would give a recommendation of 17.9 liters/s or 4.5 liters/s for each unit. Recommendations of the Western Regional Extension Service are 3.8 to 4.7 liters/s for each unit (9). The standards of the International Organization for Standardization (ISO) are (17):

\[ Q_{ISO} = \begin{cases} 
2.75 + 1.0 x_1, & x_1 < 10 \\
5.25 + .75 x_1, & x_1 \geq 10 
\end{cases} \]  
[1]

where \( Q_{ISO} \) = the recommended air flow capacity (liters/s) and \( x_1 \) = number of units.
These guidelines are conservative compared with American standards.

Spencer (10) states that although adequate pump capacity helps maintain constant line vacuum, excess pump capacity is of no benefit. The objective of this study was to measure air usages in various milking parlor situations and to recommend pump capacity standards based on those data.

MATERIALS AND METHODS

The purpose of a vacuum pump in a milking system is to remove air from the vacuum system, to provide the negative pressure needed to milk cows, and to help maintain stable line vacuum. Adequate pump capacity in a given system corresponds to that rate of air flow admitted to the system, $Q_{\text{total used}}$ (liters/s), which is admitted during milking, $Q_{\text{consumed}}$, and through leaks in the system, $Q_{\text{leaks}}$.

$$Q_{\text{total used}} = Q_{\text{consumed}} + Q_{\text{leaks}} \quad [2]$$

If pump capacity, $Q_{\text{pc}}$, exceeds air entering the system, then the remainder must be admitted through the regulator, $Q_{\text{regulator}}$, to maintain the set vacuum.

$$Q_{\text{pc}} = Q_{\text{consumed}} + Q_{\text{leaks}} + Q_{\text{regulator}} \quad [3]$$

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1. Reference to a company or product name is for specific information only and does not imply approval or recommendation of the product by Cornell University to the exclusion of others that may be suitable.

2. DeLaval high capacity orifice flow meter, Model #8300738--81; DeLaval Separator Co., Agricultural Division, Poughkeepsie, NY 12602.

3. DeLaval low capacity orifice meter, Model #830737--80; DeLaval Separator Co., Agricultural Division, Poughkeepsie, NY 12602.

4. Sentinel regulator, Model #100, Western Dairy Research, 6305 Avenue 176, Tulare, CA 93274.

5. Ion flow meter, Model #4100, Thermal Systems, Inc., 2500 Cleveland Avenue North, St. Paul, MN 55113.


7. Endevco pressure transducer, Model #8503A--15; Endevco Dynamic Instrument Division, 801 South Arroyo Parkway, Pasadena, CA 91109.

8. Brush Mark 220 recorder, Model #15--6327--50--178; Gould, Inc., Brush Instrument Division, 3631 Perkins Avenue, Cleveland, OH 44114.

9. Sentinel regulator, Model #350, Western Dairy Research, 6305 Avenue 176, Tulare, CA 93274.

To determine pump capacities used in milking parlors, $Q_{\text{total used}}$ was measured in 31 milking parlors with 4 to 40 milking units, 1 to 4 operators, and 24 to 200 cows milked per hour. Pump capacity was measured with either a high capacity orifice flow meter, or a low capacity orifice meter. For remaining measurements, regulators installed in each dairy were replaced with a Sentinel regulator mounted in an airtight Plexiglas box. An ion flow meter, attached to a single opening on the box side, continuously measured total air flow through the regulator. The negative pressure normally used by each dairy was measured with a mercury manometer, and the regulator was adjusted to that pressure. Vacuum, monitored with a pressure transducer, and air flow rate, measured with the ion flow meter, were recorded on a dual channel strip chart recorder.

$Q_{\text{leaks}}$ was determined by measuring air flow through the regulator with all pulsators and units detached. At that point $Q_{\text{consumed}} = 0$; therefore, from Equation 3,

$$Q_{\text{leaks}} = Q_{\text{pc}} - Q_{\text{regulator}} \quad [4]$$

A small portion of the difference between $Q_{\text{pc}}$ and $Q_{\text{regulator}}$ may be from frictional losses, but this is included in $Q_{\text{leaks}}$.

Air flow into the regulator then was measured during an hour of milking. With Equation 3, this measurement was used to find air consumption during milking, $Q_{\text{consumed}}$:

$$Q_{\text{consumed}} = Q_{\text{pc}} - Q_{\text{leaks}} - Q_{\text{regulator}} \quad [5]$$

Concurrently, one person observed operators during milking and recorded when units were applied and removed. The number of cows milked per hour was calculated from these figures.

Pump capacities in the 12 largest parlors exceeded the operating range of the ion flow meter, low capacity orifice meter, and Model 100 Sentinel regulator. A higher capacity orifice meter was obtained, and the Model 100 Sentinel was replaced with the Model 350. A second orifice was cut into the Plexiglas box on the opposite wall to admit one-half of the air flow through the regulator. Total air flow was determined by doubling the ion flow meter.
measurement of air flow. These modifications provided an approximate twofold increase in the capacity of the measuring system and kept the negative pressure within the enclosure (box) housing the regulator at 25 mm Hg or less.

The three instruments used to measure air flow were calibrated with a pitot tube and water manometer. Air flows measured with the large orifice meter, $Q_{lom}$, the small orifice meter, $Q_{som}$, and the ion flow meter, $Q_{ifm}$, were adjusted to pitot tube flow rates, $Q_{true}$, according to the following regression equations:

$$Q_{true} = 0.837 + 0.899Q_{lom} \text{ (liters/s)},$$

$$Q_{true} = -2.357 + 1.01Q_{som},$$

and

$$Q_{true} = 1.33 + 0.957Q_{ifm}. \quad [8]$$

For the analysis of recordings of air usage during milking, data were sampled at 5-s intervals for 30 min yielding 360 data points for each parlor. Recordings of five farms were sampled for the entire hour and the frequency of air usages compared in each .5 h. No differences were observed between .5-h intervals; therefore, a .5-h interval was sampled for the remaining parlors.

Varying air usage during milking was unrelated to $Q_{leaks}$, thus, the analysis was on air usages excluding leaks. For each farm, a histogram was drawn of frequency with which a given air usage occurred versus air usage in liters/s for each unit. Frequency was expressed as a percent of the total number of data points. Histograms illustrate how air usage during milking was distributed over time. By summing frequency percentages, a cumulative distribution curve was drawn for each farm. From averaged measures in each interval over all farms, a pooled histogram and cumulative distribution curve were drawn.

Regression analysis was used to find the relationship between air usage and number of units in the parlor, number of operators, and number of cows milked per hour.

Based on the initial analysis, farm number 31 was an outlier both in air usage and size of parlor; therefore, it was excluded from remaining analyses. From the pooled distribution curve in Figure 1, average air consumption remained at or below 1.7 liters/s for each unit 99% of the time. Air usages above 1.8 liters/s for each unit were so infrequent that they are not apparent at the scale in Figure 1. The pooled histogram and histograms for individual farms were skewed left, indicating lower air usages occurred more frequently.

Although large air usages are rare and brief events, air consumption at the 99th percentile in each parlor was used for the analysis and comparison of parlors. This is the point below which the sampled air usages remained 99% of the time.

The 99th percentile of air usage for each farm, $Q_{consumed}$, excluding air loss from leaks, was plotted against number of milking units, $x_1$, in that parlor (Figure 2), number of cows, $x_2$, milked per hour (Figure 3), and number of operators, $x_3$. Air usage increases as $x_1$, $x_2$, and $x_3$ increase.

Although air loss from leaks, $Q_{leaks}$, is a fixed air usage for a given parlor, there were wide variations among farms, from -2.2 liters/s to 15.4 liters/s, averaging 4.0 liters/s.

Figure 1. Pooled histogram and cumulative distribution curve for 30 parlors of air usage per unit versus frequency of air usage.

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1° Water manometer, Model #30EB25; The Meriam Instrument Co., Cleveland, OH 44114.
The negative value is an artifact from differences among instruments. Correlations between \( Q_{\text{consumed}} \) and \( x_1 \), \( x_2 \), and \( x_3 \) were .82, .85, and .70, respectively. Including air loss from leaks, correlations between \( Q_{\text{total used}} \) and \( x_1 \), \( x_2 \), and \( x_3 \) were .73, .80, and .66.

A linear regression model best fit the data, and resulting regression equations for air usage excluding leaks, \( Q_{\text{consumed}} \), and for air usage including leaks, \( Q_{\text{total used}} \), with one and two \( x \)-variables are:

\[
Q_{\text{consumed}} = 4.00 + .745 \, x_1 \, \text{(liters/s)} \quad [9]
\]

\[
s_y^* = 3.46
\]

\[
r^2 = .671
\]

\[
Q_{\text{consumed}} = 2.35 + .323 \, x_1 + .093 \, x_2 \quad [10]
\]

\[
s_y^* = 2.98
\]

\[
r^2 = .766
\]

\[
Q_{\text{total used}} = 7.96 + .748 \, x_1 \, \text{(leaks included)}
\]

\[
s_y^* = 4.71 \quad [11]
\]

\[
r^2 = .526
\]

\[
Q_{\text{total used}} = 5.84 + .203 \, x_1 + .12 \, x_2 \, \text{(leaks included)} \quad [12]
\]

\[
s_y^* = 4.13
\]

\[
r^2 = .649
\]

where \( x_1 \) = number of units and \( x_2 \) = cows milked per hour.

In the linear regression model, \( x_1 \) is fit first for practical reasons, although the correlation for \( x_2 \) is highest. Because recommendations have been for number of units, both dairymen and the milking machine industry think of pump capacity requirements in terms of number of units. Also, the number of milking units in a parlor is immediately apparent whereas dairymen using these recommendations may not know the number of cows milked per hour.

Second in the model sequence, cows milked per hour, \( x_2 \), explains a significant amount of the variation in air usage among farms. From observing milking routines and air flow recordings, it is logical that air usage increases with number of units and cows milked per hour, because it appeared that the most frequently recurring air usage was in changing units from cow to cow. With more units and more cows milked per hour, this usage occurred more frequently, thus increasing air usages.

The number of operators, \( x_3 \), also was related to air usage, but the relationship was based primarily on the correlation between

**Figure 2.** Air usage excluding air loss from leaks versus number of units in each parlor.

**Figure 3.** Air consumption excluding air loss from leaks versus cows milked per hour.
number of operators and cows milked per hour (.80). With an increasing number of operators, cows milked per hour generally increases. However, in an undersized parlor where the operator(s) is not employed fully, the number of operators becomes a poorer indicator of air usage. Therefore, number of operators was placed third in the model sequence to see if it explained a significant amount of variability in air usage after number of units and cows milked per hour. Since it did not add significantly to the model, x3 does not appear in the final regression equations.

The three, x1, x2, x3, do not explain all of the variability of air usage among farms. The r² ranges from .53 to .77. Air flow admitted during milking, Qconsumed, varied both within a given farm and among farms. Events affecting air usage for a given farm include putting units on cows, removing units, emptying weigh jars, units falling off or being kicked off, liner slip, machine stripping, weigh jar milk sampling, evacuating air from an automatic detacher, and pulling off a long milk tube from the milk transfer line.

Variations among farms were characterized by differences in Qconsumed and differences in frequency and distribution of air usages with time. Differences among farms reflect the variety of sampled parlors, difference in size, style, types, and brands of equipment.

Two farms (identified as #13 and #31) had unusually large air usages. Farm #31, the outlier which was excluded, had a backflushing system which required that the long milk tubes be pulled off the milk transfer line between each cow milked, briefly letting in a large rush of air. With 40 milking units and 200 cows milked per hour, these brief air usages occurred frequently. Farm #13 also had milking equipment which required removal of the long milk tubes between cows but had only eight units milking 44 cows per hour. The brief air usages were neither as large nor as frequent as for Farm #31.

Another factor affecting variation among farms is the operator's milking techniques. People vary in the care with which they handle milking units, and because shifting units is a frequent event, the amount of air used significantly may affect air usage. The operator-effect was confounded with parlor design and could not be isolated. Although unmeasured in this sample, it is likely that an operator varies from day to day in milking routine which would change the air flow required.

Cow behavior also can affect air flow used during milking. Units being kicked off or excessive liner slip can admit unusually large amounts of air.

In addition to variations in air usage during milking, air loss from leaks, Qleaks, also varied widely among farms although it is a fixed air usage in any one parlor. Variations among parlors are primarily differences in how tightly and carefully pipelines are installed. The Qleaks was low in parlors with stainless steel vacuum systems and carefully sealed joints but was much greater in parlors with poorly installed PVC pipelines and inadequately glued joints.

The amount of air loss from leaks is unrelated to number of units, cows milked per hour, or number of operators. Therefore, the correlations of Qtotal used, including Qleaks, with x1, x2, and x3 are smaller than the correlations of Qconsumed with these measures.

Predictions for air usage (Equations 9 and 11) are in a form similar to that in ISO standards. A base amount of air flow is needed for the vacuum system in addition to a per unit amount, corresponding respectively to the intercept and slope of the regression equation.

Comparison of Equations 9 and 10 with Equations 11 and 12 shows that standard errors are larger and r² smaller when Qleaks is included in the regression analysis. Also, inclusion of Qleaks does not alter the air requirement per unit but doubles the intercept or base capacity required for the system, as when Equations 9 and 11 are compared. This reflects that Qleaks is a constant within a given system and unrelated to number of units.

In Equation 9, r² = .671 and the standard deviation about the line is nearly as large as the intercept, indicating that although the number of units affects air usage, there is variability unexplained by this variable. This is expected from the numerous factors affecting air usage.

Including cows milked per hour in Equation 10 explains more of the variability in air usage among farms as indicated by r² = .766. Although inclusion of x2 decreases the intercept, the predicted Qconsumed is no less for a given number of units if milking proceeds at a reasonable speed.

As with Equation 10, adding x2 in Equation
12 decreases the intercept and coefficient for \( x_1 \), but the predicted air requirement is usually higher than with number of units alone. Compared to Equation 10, inclusion of \( Q_{\text{leaks}} \) in Equation 12 again increases the base allowance while changing the coefficients for \( x_1 \) and \( x_2 \) only slightly. The large variations among farms are reflected in large standard deviations and smaller correlation coefficients. These regression equations represent the mean 99th percentiles of air usage; thus with wide variations among farms some air usages are well above the prediction equations.

For recommended standards for adequate pump capacity in other parlors, two standard deviations (SD) could be added to Equations 9 and 10, encompassing 95% of the samples. Equation 6 becomes

\[
Q_{\text{consumed}} + 2\text{SD} = 10.92 + .745x_1
\]

Equation 7 becomes

\[
Q_{\text{consumed}} + 2\text{SD} = 8.31 + .32x_1 + .09x_2
\]

and Equation 11 becomes

\[
Q_{\text{total used}} = 7.96 + .748x_1
\]

respectively. These equations provide generous standards for pump capacity recommendations. They are higher than ISO standards, although similar in format.

Standards for pump capacity must allow for some air loss from leaks, although large leaks should be rectified rather than maintaining vacuum with a larger vacuum pump. Therefore, average \( Q_{\text{leaks}} \) of 4.0 liters/s is added to Equations 13 and 14 to give

\[
Q_{\text{consumed}} + 2\text{SD} + \text{avg leaks} = 14.92 + .745x_1
\]

and

\[
Q_{\text{consumed}} + 2\text{SD} + \text{avg leaks} = 12.31 + .32x_1 + .09x_2
\]

respectively. Possible recommendations are illustrated in Figure 4, including mean regression lines for the sampled data with and without leaks (Lines C and A, respectively). Line B represents the ISO standard which is considerably below the mean \( Q_{\text{total used}} \) of sampled parlors. Line D corresponds to Line A plus two standard deviations.
plus average $Q_{\text{leaks}}$ (Equation 15). Line E represents the common US recommendation of 4.5 liters/s for each unit. For all lines compared with Line E, the common American recommendation of 4.5 to 5.5 liters/s for each unit does not describe the relationship of air usage to number of units but markedly overestimates air requirements in large parlors. From data for projected requirements, the single value used to represent air usage in each sampled parlor was relatively inflated as it was a point that was above actual usage 99% of the time. The histograms illustrate that these large air usages are brief and infrequent events. The question must be asked, because large air usages are brief and infrequent events, is it necessary to ensure that pump capacity be above air usage at all times? The cost of initial pump purchase, maintenance, and operation must be weighed against the small likelihood that air usage will exceed the capacity recommended in Equations 15 and 16.

**SUMMARY AND CONCLUSIONS**

Air flow utilization measured in 30 milking parlors was best characterized by the regression equations

$$Q_{\text{consumed}} = 4.00 + 0.745 x_1 \ [17]$$

and

$$Q_{\text{consumed}} = 2.35 + 0.32 x_1 + 0.09 x_2 \ [18]$$

where $x_1$ = number of units and $x_2$ = cows milked per hour.

Allowance was ample for farm to farm variation with addition of two standard deviations plus average air loss from leaks to the above equations. This resulted in

$$Q_{\text{used}} = 14.92 + 0.745 x_1 \ [19]$$

and

$$Q_{\text{used}} = 12.31 + 0.32 x_1 + 0.09 x_2 \ [20]$$

where $Q_{\text{used}}$ = predicted air usage. These equations provide the best recommendations for adequate pump capacity based upon our data.

These results illustrate that:

1. Air usage during milking remains low most of the time and large air usages are rare and brief events.
2. Air usage in parlors depends primarily upon number of units and cows milked per hour.
3. Including number of operators does not add significantly to the accuracy of the prediction equation for air usage.
4. Present US recommendations for pump capacity are considerably greater than air capacity requirements measured in the systems of this study, particularly for large parlors.

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**REFERENCES**