Field Measurement of Milking Vacuum Using Flow Simulation

Steven Stewart, *DVM*
University of Minnesota
St. Paul, MN

Introduction

Many dairy veterinarians offer milking equipment evaluation to their clients as part of their routine services. While these services have usually been initiated largely for mastitis control reasons, improving milking performance is becoming a more important (and marketable) justification for these services, especially as dairies grow larger. Milking performance can be improved with proper vacuum settings and proper equipment configurations.

Much progress has been made in the past few years to simplify equipment evaluation and to clarify the analysis of the results. This paper discusses the routine field use of an artificial, portable flow simulator to measure claw outlet vacuum.[9,10]

Background

All modern milking machines utilize a vacuum inside a teat-cup liner to extract milk. Properly functioning equipment should create and maintain a teat-end vacuum at a level and degree of stability compatible with rapid, complete milk extraction and minimal tissue trauma.

Traditionally, most of the emphasis on equipment function has focused on measuring, controlling, and stabilizing system vacuum from the vacuum pump to the inlet on the milk pipeline. These efforts usually consisted of measuring and analyzing pump performance, reserve capacity, regulator closure percentage, pipe sizing, plumbing layout, and milk pipeline slope, as well as evaluation of at the pulsation system. While the function of these components may be important, nearly all of their influence ends at the inlet into the milk pipeline.

The National Mastitis Council (NMC) has published testing procedures[6] to standardize most performance measurements of these "system" and pulsation components. Therefore, there currently should be sufficient knowledge of the underlying physical principles and enough field experience with the NMC procedures to test and correct deficiencies arising with the system or pulsation components. Since these procedures have been well documented, problems arising from these areas will not be discussed.

Much of the final performance of the equipment however is determined by the configuration of the components that lie in the direct path of milk from the teat-end to the milk inlet. These components include such things as teat-cup liners, short milk tubes, claw ferrules, air admission vents, claw size, claw design, claw outlet diameter, milk hoses, milk inlets, and other additional components such as milk meters, shut-offs, and sensors. These components often are more critical to achieving the final claw outlet vacuum goal than the more traditionally measured components.

Experimental evidence and field experience have shown that a vacuum level of 10.5-12.5 inches Hg at the teat-end during peak milk flow offers the best combination of rapid, complete milk removal with minimal physical harm and highest milk quality.[2] On a given cow, the flow rate of milk from the teat-end is directly related to vacuum level, until approximately 40 kPa (11.8" Hg), the point at which the orifice is maximally distended, resulting in maximal cross-sectional area of the teat opening.[4]

Further increases in vacuum beyond 11.8" Hg at the teat-end have relatively small effects on milking speed, largely by increasing the velocity of the milk stream through the teat orifice, not by an increase in orifice diameter. A narrower range of 12.0-12.5 inches Hg has been suggested by Mein[2] and adopted by the authors and others. In this paper, outlet vacuum will be used as a proxy for teat-end vacuum.

Portable, Artificial Flow Simulator Design

Field measurement of claw outlet vacuum level traditionally has been done with the unit attached to a cow during an actual milking. Those working with milking equipment in the field recognize there are limitations to this approach, including interference with the milking process, excitement of the animals due to a stranger, interference with observation of milking procedures, and the differences in rates of milk flow from one cow to another. Therefore, there is a great need to be able to measure claw outlet vacuum more accurately and repeatably, without interfering with milking procedures or disturbing animals. Portable, artificial flow simulation has been a very useful tool to achieve these goals.

A device useful in testing claw outlet vacuum has been developed. The test equipment consists of a liquid flow meter (0 to 2.2 gal/min) with a valve (Dwyer Instruments, Inc./Michigan City, IN/Model #RMC142-SSV) and an artificial udder equipped with four artificial teats (Jenny-Lynn Flow Simulator, Rocky Ridge Veterinary Service, Hazel Green. WI) similar to the design specified in the relevant ISO standard.[1] It is also assumed that a cold water/air mixture has a coefficient of friction, an average density, and viscosity similar enough to a warm milk/air mixture for field purposes.

This setup was tested against an exact replica of the ISO artificial udder at the University of Wisconsin Milking Laboratory; measurements were in close agreement. The major difference between this simulator and the laboratory's is the laboratory setup uses water under pressure to the meter, while the field simulator utilizes an open bucket. This design difference has little impact on the mean vacuum simulator. The difference in measured vacuum fluctuation is dependent on claw design and on pulsation characteristics, but the difference does not seem large enough to be of major importance. It is not clear at present which system more closely mimics the degree of vacuum fluctuations introduced by a milking cow, so caution should be used when interpreting vacuum fluctuation measurements using either system.

Before using this device, it is necessary that the system has been evaluated to determine that there is enough effective reserve and sufficient milk line slope to maintain system vacuum within 0.6" Hg. of the preset operating vacuum when testing one unit at 1.5 gallons liquid flow per minute. This is easily measured by monitoring vacuum on the milk line at a point other than the unit under test. If there is more than a 0.6" Hg drop at the milk line reference point, system sources of vacuum drops need to be diagnosed using NMC guidelines and addressed to distinguish them from local milkpath source vacuum drops.[6]

Claw Outlet Measurements Using a Flow Simulator

Measurements of claw outlet vacuum levels should include:

1. Measure claw outlet vacuum at three standard rates of expected milk flow per claw:
   a. Average-3.5 Liters/minute (1.0 gal./minute).
   b. Maximal-5.5 Liters/minute (1.5 gal/minute).
   c. If possible, a specific flowrate similar to the mean peak flowrate for the herd.

These levels are based on research showing average flow rates to be approximately 1.0 gallons per minute and faster animals to be about 1.5 gallons per minute.[3]

2. Measure vacuum levels at points in the path between claw and milk line, using a standard 5/8" testing tee with a filter (Gelman Acrodisc CR PTFE 0.45 micrometer filter) at the point in question, as described by Reinemann *et al*, 1996[8] The vacuum level at each point can be compared with the milk line vacuum reference point and to other points to determine the degree of vacuum drop that is occurring between any two points.
   a. Reference point: Milk line vacuum at point other than current stall & unit.
   b. At claw outlet.

c. Immediately prior to milk inlet on unit being tested.
d. Before each component in path between claw and line.
e. After each component in path between claw and line.
3. Remove or add components. Example: DHIA testday meters. Repeat steps 1& 2.
4. Change hose length or configuration. Repeat steps 1 & 2.

Factors Determining Final Claw Outlet Vacuum Levels

The point of highest vacuum in the direct path of milk from the teat-end to the milk pipeline will be at the inlet into the milk pipeline. The final claw outlet vacuum is determined by a combination of factors that cause the vacuum level to fall. Some of these factors include:

1. The vacuum level at the inlet into the milk pipeline vacuum.

A higher vacuum level at the milk pipeline will result in a higher teat-end vacuum.

2. The flow rate of milk from the cow.

On a given cow, the flow rate of milk from the teat-end is directly related to vacuum level. Higher vacuum levels will lead to higher flow rates. However, a higher flow rate increases frictional losses within the components and losses due to lift, lowering the vacuum level. This drop will in turn lead to a lower flow rate. This cycle is repeated until an equilibrium is reached.

Since it is quite difficult to measure the actual flow rate of a cow in field conditions, often what can result in marginal systems is slow milking cows with claw outlet vacuums levels in the range of 10" Hg. This can lead to a false diagnosis of "slightly" low, but adequate, vacuum levels.

3. Frictional losses when moving the milk / air mixture.

The degree of this vacuum drop will be determined by the capacity of the local milkpath components to move the extracted milk into the milk pipeline. The diameter of milk hose, length of milk hose, smoothness of milk hose interior, turns, and other points of restriction are factors that determine the capacity. In addition, the amount of both milk and air transported per minute, as well as the ratio of the two, will determine the magnitude of these vacuum drops.

4. Energy needed to overcome gravity when lifting milk from the claw to milk line.

Roughly, if 1.5 gallons of milk per minute are being transported, there will be 0.20-0.30: Hg vacuum drop for each foot of lift required. Note that if additional hose is required, there will be an additional vacuum drop due to friction within the hose.

5. Air admission (air admitted into same unit under test)

A small amount of air admission into the claw is quite beneficial to reducing the frictional and lift losses when moving milk, as air admission allows a "slug" of milk to be transported rather than a solid column of milk. Excessive air admission, however, is detrimental, as the air speed increases to the point where the milk slug is disrupted. Sources of air admission into the unit being tested include:

a. Planned air admission.
Claw vent (or short milk tube vents).
Milk meter air vents.
b. Unplanned, steady leakage of air.
Cracks in claw bowl or leaks in claw shutoffs, holes in liners or hoses.
Leaks at milk line inlets and other claw-to-milk line locations.
c. Unplanned, sporadic leakage of air.
Unit fall-offs or air admission with unit removal or unit application.
Liner slips.

Published Standards for Evaluation

ISO (1) has published a clause relevant to the amount of acceptable vacuum drop introduced by a local milkpath component:

"Devices, including necessary connecting tubes, fitted in a long milk tube, shall not cause an additional vacuum drop of more than 5.0 kPa (1.5 in Hg) measured in the cluster (at a milk flow rate of 5.0 kg/min (11 lb/min) and an airflow of 8.0 L/min (0.3 ft^3/min)), compared with the same milking unit without those devices, when measured in accordance with ASAE EP445. Milk meters used at every milking shall comply with this requirement. Those used periodically should also comply with this requirement."

Similarly, ASAE[7] has published a relevant clause:

"No device or devices (including sight glasses) which form part of the installation and which cause a total vacuum difference greater than 3.0 kPa (0.9 in. Hg) at a milk flow rate of 3.0 kg/min (6.6 lb/min) shall be fitted between the cluster and the milking pipeline. This requirement shall not apply to independent and milk transport milking machines. Milk meters used at every milking shall comply with this requirement. Those used periodically, for example, for official milk recording, should also comply with this requirement if possible."

Results Showing Effects of Flow Rate, Hose Length, and Lift on Claw Outlet Vacuum

The following tables and graphs were created using a Tri-Scan (Babson Bros. Co., Naperville, IL) vacuum recorder and the Jenny-Lynn flow simulator. The data were exported from the Tri-Scan as a ASCII file and imported into a spreadsheet. All vacuum drops in the tables are expressed as inches Hg. Line vacuum is 15" Hg in all of the examples; the point of measurement is the claw outlet.

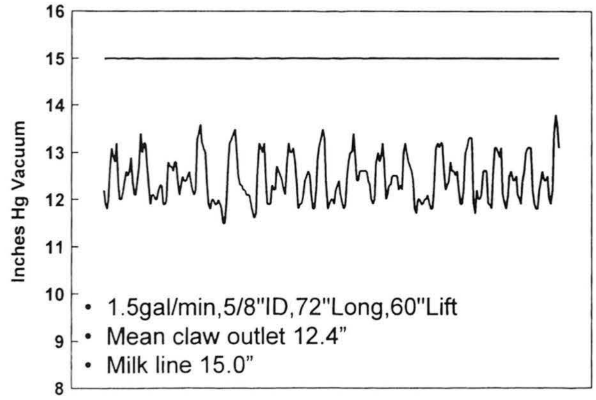
Table 1. Effects on vacuum level by changing hose length, internal diameter of hose, and height of lift.

Exp#	Hose ID (in)	Hose Lngth (in)	Lift (in)	Flow rate (g/min)	Max Vac ("Hg)	Min Vac ("Hg)	Avg Vac ("Hg)	Diff. from line ("Hg)	Drop per ft of lift ("Hg)	Frict. Drop per ft hose ("Hg)
1	5/8	72	60	1.5	13.9	11.5	12.4	2.6		
2	9/16	72	60	1.5	13.5	10.8	11.9	3.1		
3	5/8	96	60	1.5	13.5	11.3	12.2	2.8		0.10
4	5/8	96	0	1.5	14.6	12.8	13.7	1.3		0.16
5	5/8	72	0	1.5	14.9	12.8	13.9	1.1		0.18
6	5/8	48	0	1.5	15.0	13.2	14.2	0.8		0.20
7	5/8	96	72	1.5	12.8	10.6	11.9	3.1	0.30	
8	5/8	96	48	1.5	13.6	11.5	12.4	2.6	0.33	
9	5/8	96	24	1.5	14.5	12.1	13.2	1.8	0.25	
10	5/8	96	24" drop	1.5	15.0	13.2	14.0	1.0	0.15 gain	
11	5/8	96	72" drop	1.5	15.3	14.2	14.7	0.3	0.13 gain	

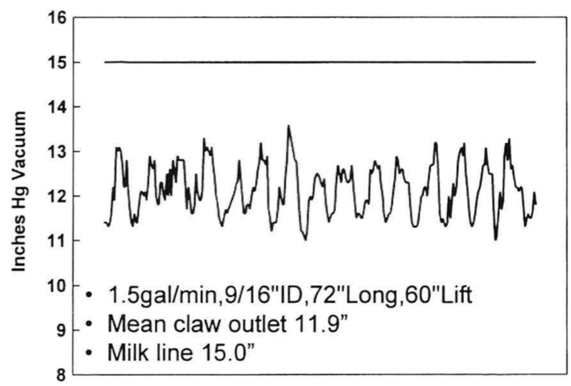
Table 2. Effects on vacuum level by changing flow rate, claw air admission, and adding a DHIA meter.

Exp#	Hose ID (in)	Hose Lngth (in)	Lift (in)	Notes	Flow rate (g/min)	Max Vac ("Hg)	Min Vac ("Hg)	Avg Vac ("Hg)	Diff from line ("Hg)	Diff. from refer. ("Hg)
12	5/8	96	84	Reference	1.5	12.6	10.9	11.6	3.4	0.0
13	5/8	96	84	No Flow	0.0	15.0	14.8	14.9	0.1	+3.3
14	5/8	96	84	1.0g/min	1.0	13.4	11.6	12.3	2.7	+0.7
15	5/8	96	84	AirVent Blocked	1.5	10.8	8.5	9.1	5.9	2.5 drop
16	5/8	96	84	DHI Meter	1.5	11.6	8.9	9.7	5.3	1.9 drop

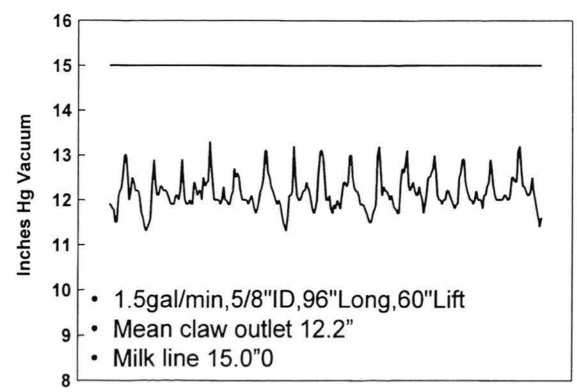
Some conclusions can be drawn from these graphs and tables: 1) Drops due to friction within a 5/8" milk hose are about 0.1"-0.2" Hg per foot of hose at a flow rate of 1.5 gal/min; at 1.0 gal/min the drop is 1/2 to 2/3 of the 1.5 gal/min drop. 2) Drops from lifting milk are approximately 0.25"-0.33" Hg per foot of lift. 3) A blocked air vent has a marked effect on vacuum level, causing an additional drop of 2.5" Hg at a flow rate of 1.5 gal/min. 4) A milk measuring device such as a DHIA meter can cause a marked vacuum drop, e.g., 1.9" additional drop at 1.5 gal/min in this example. This could lead to slower milking on test day unless system vacuum levels are raised. These results can be compared to the ISO and ASAE clauses concerning vacuum drops.



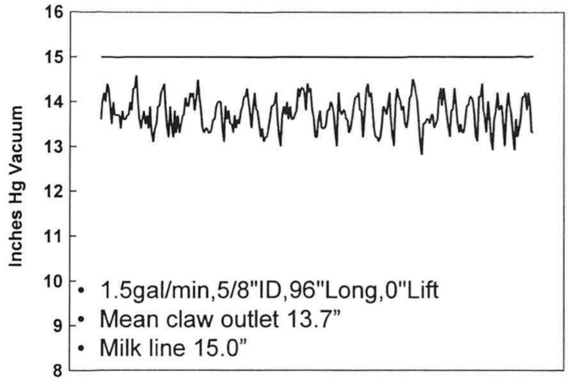
Example 1. This graph shows the effect on vacuum level at the claw outlet with 72" of 5/8" ID milk hose, 60" lift, and 1.5 gal/min of liquid flow. Mean claw outlet vacuum is 12.4" Hg. This 2.6" Hg drop is due to claw air admission, lift, and friction effects in milk hose.



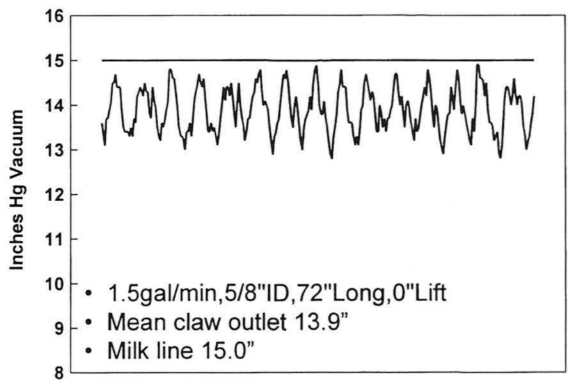
Example 2. Test configuration: 72" of 9/16" ID milk hose, 60" lift, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 11.9" Hg. This 3.1" Hg drop is due to claw air admission, lift, and friction effects in the milk hose. Compare to Example 1.



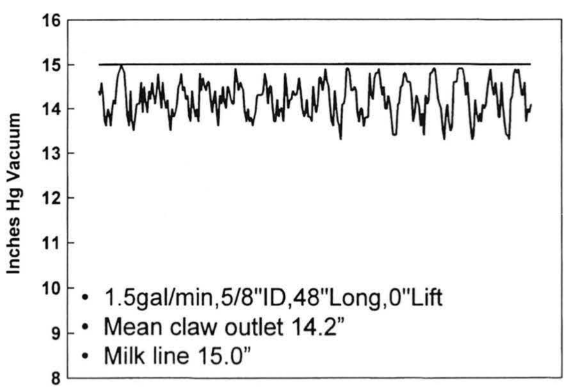
Example 3. Test configuration: 96" of 5/8" ID milk hose, 60" lift, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 12.2" Hg. This 2.8" Hg drop is due to claw air admission, lift, and friction effects in the milk hose. Compare to Example 1.



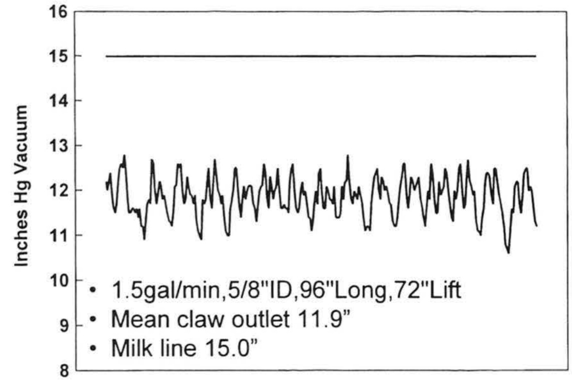
Example 4. Test configuration: 96" of 5/8" ID milk hose, no lift, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 13.7" Hg. This 1.3" Hg drop is due to claw air admission, and friction effect in the milk hose. Compare to Example 3.



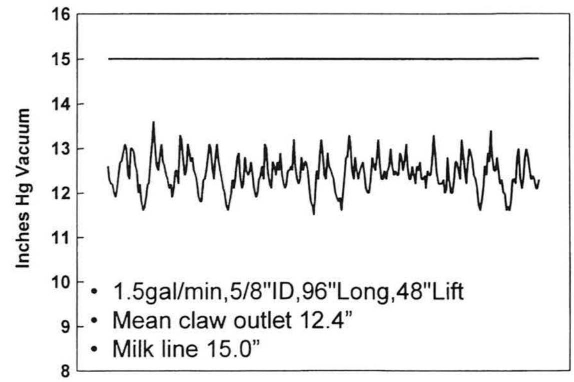
Example 5. Test configuration: 72" of 5/8" ID milk hose, no lift, and 1.5 gal/min of liquid flow. Mean claw outlet vacuum is 13.9" Hg. This 1.1" Hg drop is due to claw air admission and friction effects in milk hose. See Example 4.



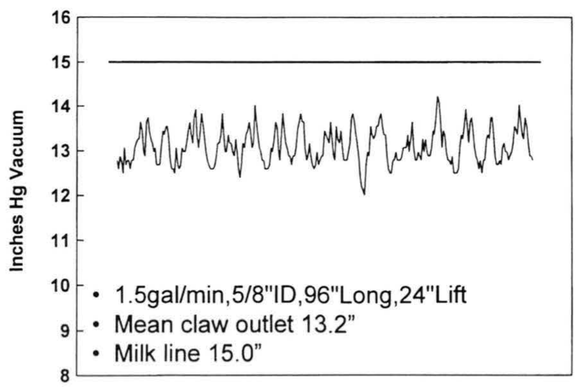
Example 6. Test configuration: 48" of 5/8" ID milk hose, no lift, and 1.5 gal/min of liquid flow. Mean claw outlet vacuum is 14.2" Hg. This 0.8" Hg drop is due to claw air admission and friction effects in milk hose. See Examples 4&5.



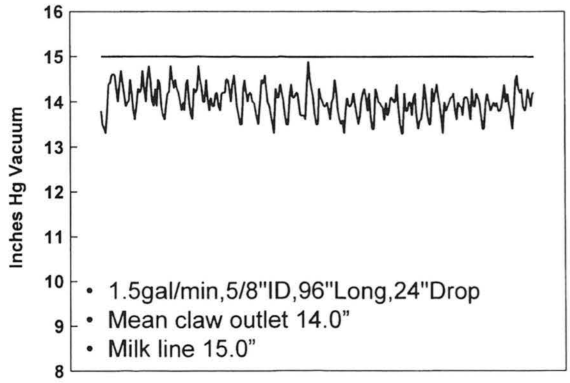
Example 7. Test configuration: 96" of 5/8" ID milk hose, 72" lift, and 1.5 gal/min of liquid flow. Mean claw outlet vacuum is 11.9" Hg. This 3.1" Hg drop is due to claw air admission, lift, and friction effects in milk hose. See Example 4.



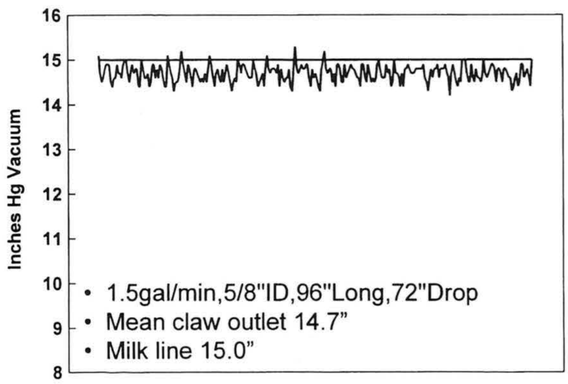
Example 8. Test configuration: 96" of 5/8" ID milk hose, 48" lift, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 12.4" Hg. This 2.6" Hg drop is due to claw air admission, lift, and friction effects in milk hose. See Example 4&7.



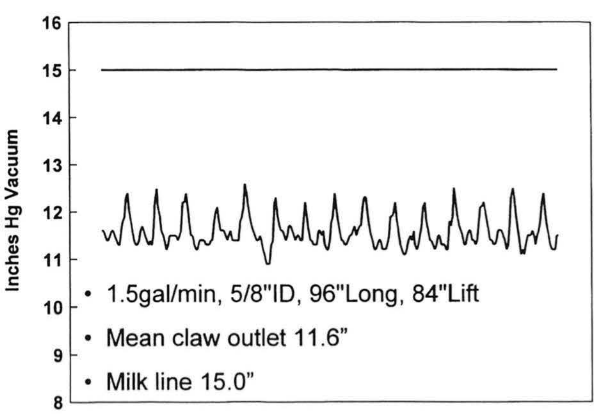
Example 9. Test configuration: This graph shows the effect on vacuum level at the claw outlet with 96" of 5/8" ID milk hose, 24" left, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 13.2" Hg versus 15.0" Hg on the line. This 1.8" Hg drop is due to claw air admission, lift, and friction effects in milk hose. Compare to Examples 7&8.



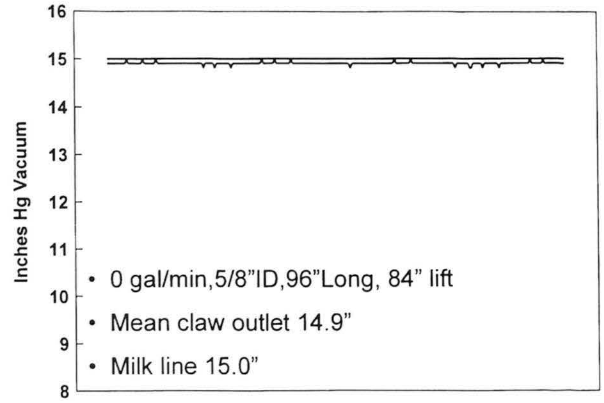
Example 10. Test configuration: This graph shows the effect on vacuum level at the claw outlet with 96" of 5/8" ID milk hose, 24" **drop**, and 1.5 gallons/minute of liquid flow. Mean claw outlet vacuum is 14.0" Hg versus 15.0" Hg on the line. This 1.0" Hg drop is due to claw air admission, drop, and friction effects in milk hose. See Examples 4 & 7.



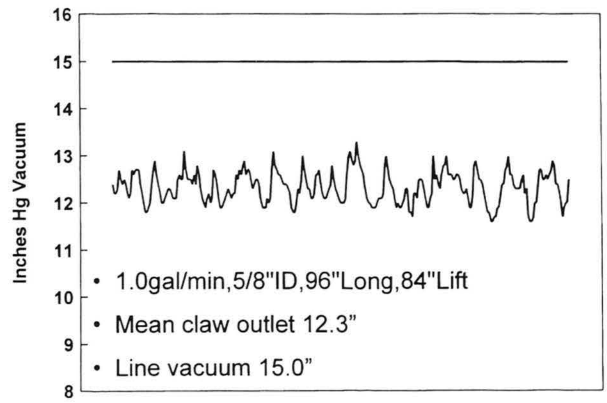
Example 11. Test configuration: 96" of 5/8" ID milk hose, 72" **drop**, and 1.5" gal/min of liquid flow. Mean claw outlet vacuum is 14.7" Hg. This 0.3" Hg drop is due to claw air admission and friction. Compare to Example 10.



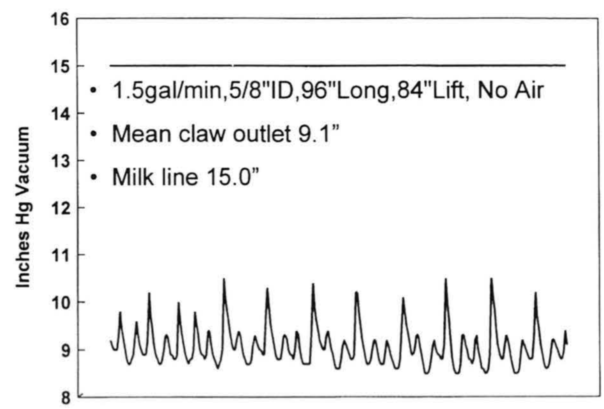
Example 12. Test configuration: 96" of 5/8" ID milk hose, 84" lift, and 1.5 gal/min liquid flow. Mean claw outlet vacuum is 11.6" Hg. This 3.4" Hg drop is due to claw air admission, lift, and friction effects in milk hose. Use as reference for Examples 13-16.



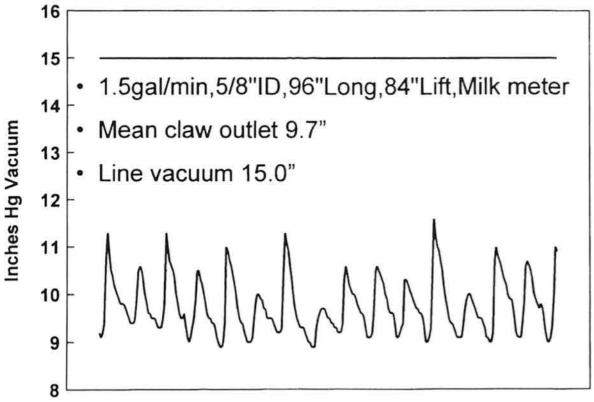
Example 13. Test configuration: 96" of 5/8" ID milk hose, 84" lift, and no liquid flow. Mean claw outlet vacuum is 14.9" Hg. This 0.1" Hg drop is due to claw air admission.



Example 14. Test configuration: 96" of 5/8" ID milk hose, 84" lift, and 1.0 gal/min of liquid flow. Mean claw outlet vacuum is 12.3" Hg. This 2.7" Hg drop is due to claw air admission, lift, and friction effects in milk hose.



Example 15. Test configuration: 96" of 5/8" ID milk hose, 84" lift, 1.5 gal/min of liquid flow. With the claw air vent blocked. Mean claw outlet vacuum is 9.1" Hg versus 15.0" Hg on the line. This 5.9" Hg drop is due to lift and friction. Compare to Example 12.



Example 16. Test configuration: 96" of 5/8" ID milk hose, 84" lift, 1.5 gallons/minute of liquid flow, with a DHIA milk meter. Mean claw outlet vacuum is 9.7" Hg versus 15.0" Hg on the line. This 5.3" Hg drop is due to claw air admission, lift, and friction effects in milk hose and milk meter.

Discussion of Field Applications of Flow Simulation

Much of the value of using flow simulation lies in consultant and client education by demonstrating the effects on claw outlet vacuum level of various factors such as peak liquid flow rate, hose length and diameter, non-hose local milkpath components (e.g., sensors), special components such as DHIA test meters, height lifted, air admission into claw, and system vacuum level. The effects on mean vacuum levels of each of these factors, collectively and isolated, can be measured more precisely and more quickly at a convenient time of time that does not interfere with normal milking procedures (or the observation of these procedures) and with no danger to an animal.

Furthermore, if the average claw outlet vacuum levels have been determined using the flow simulator at known flow rates (typically, 1.0 and 1.5 gallons per minute), the flow rate of animals in the herd can be determined by comparing the average claw outlet vacuum level at peak flow rate during actual milking. This can help determine in a more quantitative manner if premilking stimulation and procedures are adequate for optimal letdown. These graphs can be used to motivate milkers to improve procedures.

References

1. ISO. 1995. Milking Machine Installations-Construction and Performance (Final draft standard dated 08/16/95). ISO/DIS 5707. International Standards Organization, Geneva, Switzerland. 2. Mein, G.A. 1995. Design and Performance of Milking Systems. Proceedings 2nd Western Large Herd Dairy Management Conference, Las Vegas, NV. 3. Stewart, S., P. Billon, and G.A. Mein. 1993. Predicted Maximum Milk Flow Rates in Milking Systems. Proc. 32nd Annual Meeting, National Mastitis Council. 4. Williams, D.M. and G.A. Mein. 1986. The Bovine Teat Canal: Information from Measurement of Velocity of Milk Flow from the Teat. Journal of Dairy Research, 53: 179-185. 5. Johnson, A., Stewart, S., Reinemann, D.J., and G.A. Mein. 1994. Factors Affecting Vacuum Level and Vacuum Stability in the Milking Cluster. ASAE paper No. 943750. American Society of Agricultural Engineers, St. Joseph, MI. 6. NMC. 1995. Evaluation of Vacuum Levels and Air Flow in Milking Systems-Report of NMC Machine Milking Committee, National Mastitis Council, Kansas City, MO. 7. ASAE. 1992. Milking Machine Installations: Construction and Performance. ASAE standard S518. American Society of Agricultural Engineers, St. Joseph, MI. 8. Reinemann, D.J., K. Muthukumarappan, and G.A. Mein. 1996. Equipment specifications and methods for dynamic testing. Proc. 35th Annual Meeting, National Mastitis Council, Nashville, TN. 9. Stewart, S., *et al.* 1996. Field Measurement of Vacuum Levels Using a Portable Liquid Flow Simulator. Proc. 35th Annual Meeting, National Mastitis Council, Nashville, TN. 10. Stewart, S. 1997. Vacuum Level Measurement Using Flow Simulation. Proc. 36th Annual Meeting, National Mastitis Council, Albuquerque, NM.