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ORIGINAL ARTICLE

Analysis of factors affecting milking claw vacuum levels using a simulated milking device

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ABSTRACT

Bovine mastitis is typically caused by microbial infection of the udder, but the factors responsible for this condition are varied. One potential cause is the milking system, and although previous studies have investigated various methods for inspecting these devices, most have not assessed methods for evaluating the milking units. With this in mind, we analyzed the factors that affect the vacuum inside the milking claw by using a simulated milking device and by measuring milking claw vacuum when adjusting the flow rate in five stages. The factors analyzed in each milking system were the vacuum pressure settings (high and low line system) , milk tube length (200-328 cm), aperture diameter (14-22.2 mm), constricted aperture diameter (12 mm), tubing configurations, lift formation (0-80 cm), claw type (bottom and top flow) and use or non-use of a milk sampler. The study findings demonstrated that all of these variables had a significant impact on claw vacuum and suggest that a diagnostic method using a simulated milking device should be considered when inspecting modern milking systems.

Key words: *bovine mastitis, claw vacuum, milking system inspection method, milking unit, simulated milking device.*

INTRODUCTION

Bovine mastitis (BM) is the most costly condition affecting dairy cows. Since the causes of BM are varied, prevention requires careful consideration of all relevant risk factors, including the dairy farm's cattle shed facilities, animal management practices, milking procedure and milking system.

Many of the studies that examined the causes of mastitis have focused on milking procedure (Neave *et al.* 1969; Bramley *et al.* 1996; Barkema *et al.* 1998, 1999) and milking systems that come into direct contact with and affect the teat (Mahle *et al.* 1982; Baxter *et al.* 1992; Rasmussen & Madsen 2000; Ambord & Bruckmaier 2010; Sterrett *et al.* 2013). In Japan, M. Enokidani (2006, unpublished data) stated that milking system issues consisted of a combination of those that were present at the time of system installation and those that arose afterwards due to poor maintenance. In that study it was found that only eight out of 136 inspected milking systems (6%) were operating properly.

In any milking system, numerous points exist at which vacuum measurements can be undertaken. In addition, once such data has been collected, it can be averaged and analyzed in a variety of different ways. The Procedures for Evaluating Vacuum Levels and Airflow in Milking Systems (National Mastitis Council (NMC), 2004) developed by the Machine Milking Committee of the NMC, are based on ASAE (American Society of Agricultural Engineers) (ASAE 1996) and International Standards Organization (ISO 1996) standards. These NMC procedures describe the accepted methodology for assessing milking system performance and for interpreting the obtained test results. Inspections of milking systems can be conducted based on visual testing (i.e. assessment of tube deterioration, condition of rubber liners, claws and tubing configuration), inspection-based testing of milking procedures and cattle handling practices, inspection-based testing of milking system operation when not attached to the animal (static testing), and testing conducted during actual milking (dynamic testing). Although passing all of the tests is a necessary precondition, it is not sufficient for avoiding BM. Visual testing is, as the name implies, based on visual inspection, so considerable knowledge and experience is required to identify problems. Static testing only diagnoses the flow of air through the tubing and does not examine milk flow during milking, so it is incapable of assessing milking unit components from the milk line to the claw. While dynamic testing does assess milk flow during milking,

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the amount of milk obtained from a dairy cow using milking equipment is regarded as the milk yield, and this yield differs on a daily basis so it is not possible to obtain a consistent yield in each test (i.e. to test the same load on the same milking equipment). Even if the equipment passes dynamic testing during a low yield, there is no guarantee that a similar result will be obtained for a high yield. The simulated milking test enables a consistent load every time and, although water does not have the same fluid properties as milk, this test can assess milking unit components during simulated dynamic operation while ensuring the same flow rate (load).

In the present study, we used a simulated milking device to demonstrate problems with milking unit components that cannot be assessed in inspections using a standard milking system.

MATERIALS AND METHODS

Simulated milking device

The simulated milking device was a Jenny Lynn Flow Simulator (Rocky Ridge Dairy Consulting, Hazel Green, WI, USA) comprising buckets with flow meters at one end and a flow diverter with four simulated teats attached at the other end (Fig. 1). The flow rate of the simulator could be adjusted to arbitrarily determine the simulated milk yield. Simulated teats were placed on the four liners in the same manner as during actual milking and fixed with adhesive tape to prevent liner slip. Flow rates were measured at 1.9 kg/min, 3.8 kg/min, 5.7 kg/min, 7.6 kg/min and 8.7 kg/min, and these flow rates were adjusted at 30 sec after starting simulated milking. Mean claw vacuum (claw vacuum) was measured for 2 min after this 30 sec period using a vacuum measurement device (Triscan, Surge: Babson Bros. Co., Naperville, IL, USA).

This study was performed upon various dairy farmer systems in different farms each item.

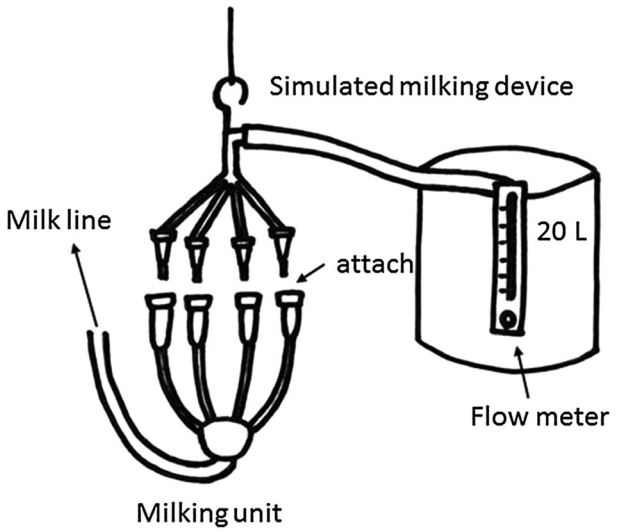

Figure 1 Simulated milking device.

Tubing system differences

Claw vacuum was measured with the simulated milking device for 2 min at the five flow rates using various dairy farmer systems, namely a highline system (aperture diameter: 16 mm), a highline system with detacher (aperture diameter: 16 mm), a lowline system (aperture diameter: 16 mm) and automatic detacher, a low line system (aperture diameter: 22 mm) and automatic detacher, and a dual series vacuum system (aperture diameter: 16 mm).

Milk tube length (highline)

Claw vacuum at five flow rates was measured in the highline system for 2 min using the simulated milking device after changing to long milk tubes with an aperture diameter of 16 mm and lengths of 248 cm, 288 cm, 317 cm (automatic detacher) and 328 cm.

Milk tube length (lowline)

Claw vacuum at five flow rates was measured in the lowline system for 2 min using the simulated milking device after changing to long milk tubes with an aperture diameter of 16 mm and lengths of 200 cm, 250 cm and 300 cm.

Milk tube constricted aperture diameter

Claw vacuum at five flow rates was measured in the highline system for 2 min using the simulated milking device in a 288 cm-long milk tube (aperture diameter: 16 mm) fitted with a mastitis detector (Ambic Equipment Ltd., Oxfordshire, UK) and a single tube with a length of 12 mm and aperture diameter of 16 mm inserted at 10 cm intervals.

Milk tube aperture diameter

Claw vacuum at five flow rates was measured in the lowline system for 2 min with the simulated milking device using a fixed long milk tube length of 200 cm and three aperture diameters of 14 mm, 16 mm and 18 mm.

Difference between horizontal and vertical tubing configurations

Claw vacuum at five flow rates was measured in the lowline system for 2 min with the simulated milking device for a vertical tubing configuration (standard milking specification: −87 cm elevation difference) in which a 200 cm-long milk tube (16 mm aperture diameter) ran downward from the claw at the top of the milking stall to the milk line, and a horizontal tubing configuration in which a long milk tube with the same length and aperture diameter ran sideways along the milking pit floor from the claw to the milk line.

Differences in lift height: using a long milk tube with a length of 300 cm and aperture diameter of 16 mm, lift (the condition where the milk rises against gravity) was created by forming an undulating shape with heights of 0 cm, 20 cm, 40 cm, 60 cm and 80 cm, and claw vacuum

was then measured in the lowline system at five flow rates for 2 min using the simulated milking device.

Claw type and milk sampler setup

Claw vacuum at five flow rates was measured in the lowline system for 2 min using the simulated milking device in four configurations, specifically a top-flow milking claw, bottom-flow milking claw, and with and without a milk meter sampler.

RESULTS

Tubing system differences

Claw vacuum in the highline system dropped dramatically below the designated pressure (50 kPa) as the flow rate increased, and at a flow rate of 8.7 kg/min it had dropped to 31.7 kPa. This was even lower when the automatic detacher was fitted. Claw vacuum in the lowline system decreased gradually as the flow rate increased and was 39.7 kPa and at a flow rate of 8.7 kg/min, which was vastly less of a decrease than in the highline system. At an aperture diameter of 22.2 mm, the claw vacuum in the lowline system was virtually unchanged, even as the flow rate increased. In the dual-series vacuum system, claw vacuum was maintained at close to the designated pressure at 44.7 kPa up to a flow rate of 5.7 kg/min, but decreased sharply thereafter (Fig. 2).

Milk tube length (highline)

Claw vacuum in the highline system decreased as the milk tube length and flow rate increased and when the automatic detacher was fitted (317 cm), the vacuum level decreased more than in the longest tube (328 cm) at each flow rate (Fig. 3).

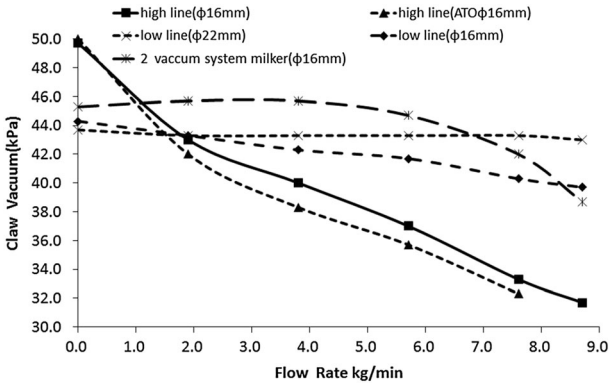

Figure 2 Variation in claw vacuum with different tubing system configurations. Comparison of claw vacuum levels by milk line tubing configuration system. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). High line: milk tube length, 300 cm; aperture diameter, 16 mm; milk line height, 180 cm. High line: milk tube length, 371 cm; aperture diameter, 16 mm; milk line height, 181 cm; automatic detacher fitted. Low line: milk tube length, 235 cm; aperture diameter, 22.2 mm; milk line height, -60 cm. Low line: milk tube length, 200 cm; aperture diameter, 16 mm; milk line height, -90 cm. Dual-series milker: milk tube length, 280 cm; aperture diameter, 16 mm; milk line height, 191 cm. ATO, automatic take off.

Milk tube length (lowline)

Claw vacuum in the lowline system decreased gradually as the milk tube length and flow rate increased, and at the maximum flow rate of 8.7 kg/min claw vacuum was 35.7 kPa at 200 cm, 33.7 kPa at 250 cm and 32.3 kPa at 300 cm (Fig. 4).

Milk tube constricted aperture diameter

In terms of claw vacuum in the highline system by constricted aperture diameter, the rate of decrease became greater as the aperture diameter became thinner, and dropped the most when the mastitis detector was

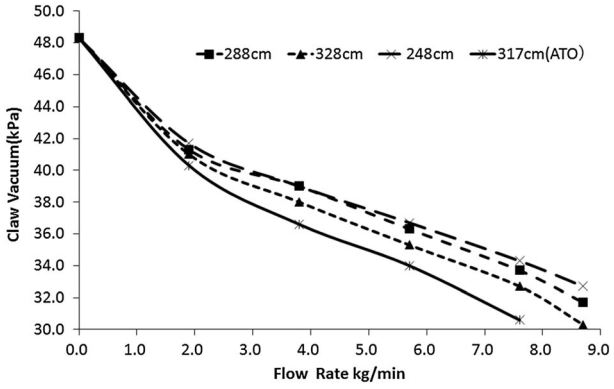

Figure 3 Variation in claw vacuum with milk tube length on a highline system. Effect of milk line length on claw vacuum level at a highline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 288 cm; aperture diameter, 16 mm; milk line height, 170 cm 317 cm (AR): milk tube length, 317 cm; aperture diameter, 16 mm; milk line height, 181 cm. ATO, automatic take off.

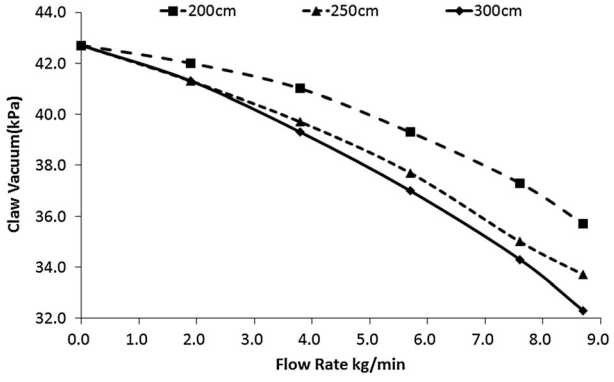

Figure 4 Variation in claw vacuum with a milk tube length on a lowline system. Effect of milk tube length on claw vacuum level at a lowline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 200–300 cm; milk line height, -87 cm; aperture diameter, 16 mm.

attached. Claw vacuum levels at the maximum flow rate of 8.7 kg/min were 31.7 kPa at a 16 mm aperture diameter, 30.3 kPa at 12 mm, and not measurable when the mastitis detector was fitted (Fig. 5).

Milk tube aperture diameter

Claw vacuum in the lowline system decreased as the long milk tube aperture diameter became thinner and the flow rate increased. Claw vacuum levels at the maximum flow rate of 8.7 kg/min were 30.7 kPa at an aperture diameter of 14 mm, 36.0 kPa at 16 mm, 39.7 kPa at 18 mm and 43.0 kPa at 22.2 mm. At an aperture diameter of 22.2 mm, claw vacuum was virtually unchanged at each flow rate (Fig. 6).

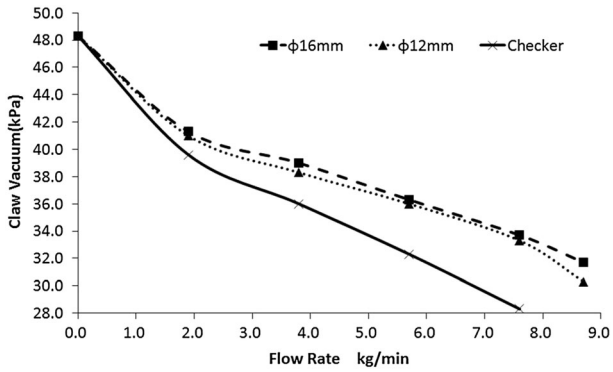

Figure 5 Variation in claw vacuum with a narrow point in a milk tube on a highline system. Effect of milk tube constrictions on claw vacuum level on a highline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Measurements were performed after placing a short 10 cm tube with an aperture diameter of 12 mm and a mastitis detector along the 288 cm milk tube; milk line height, 170 cm; aperture diameter, 16 mm.

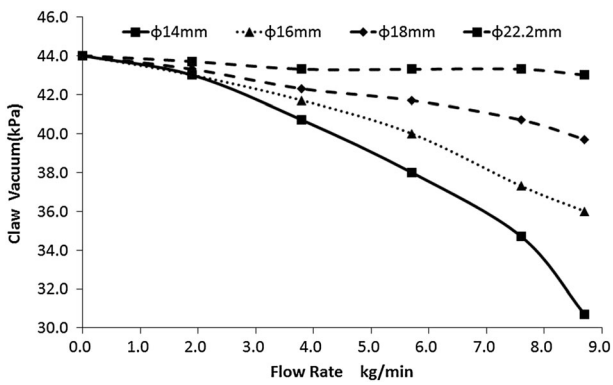

Figure 6 Variation in claw vacuum with milk tube diameter on a lowline system. Effect of milk tube aperture diameter on claw vacuum level at a lowline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 200 cm; milk line height -87 cm; aperture diameters, 14 mm, 16 mm, 18 mm, 22.2 mm.

Differences between horizontal and vertical tubing configurations

Claw vacuum levels in the lowline horizontal and vertical tubing configurations decreased at a lesser rate than those of the vertical tubing configurations. Claw vacuum levels at the maximum flow rate of 8.7 kg/min were 36.0 kPa for the 16 mm aperture vertical configuration and 34.0 kPa for the 16 mm horizontal configuration (Fig. 7).

Differences in lift height

Claw vacuum levels in the lowline system decreased as the flow rate increased in a manner that was proportional to lift height. Claw vacuum levels at the maximum flow rate of 8.7 kg/min were 36.0 kPa at a height of 0 cm, 35.3 kPa at 20 cm, 35.0 kPa at 40 cm, 34.0 kPa at 60 cm and 33.0 kPa at 80 cm (Fig. 8).

Claw type and milk sampler setup

Claw vacuum levels in the lowline system were higher at each flow rate for the bottom-flow milking claw than for the top-flow milking claw, regardless of whether or not a sampler was used. Claw vacuum decreased more significantly when a sampler was fitted than when a sampler was not fitted, regardless of the claw type (Fig. 9).

DISCUSSION

The standard pressure setting in a highline milking system is 50 kPa, while the standard pressure setting in a lowline milking system is 42–46 kPa. Schuring and Reinemann (2005) reported that a claw vacuum between 35 and 42 kPa was optimal during milking at peak yield to ensure good milking characteristics and teat

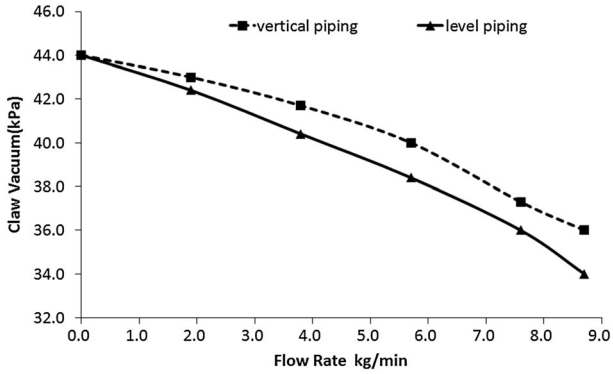

Figure 7 Variation in claw vacuum with piping on a lowline system. Effect of milk tube configuration on claw vacuum level. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 200 cm; aperture diameter, 16 mm; milk line height, -87 cm. Vertical tubing: standard lowline tubing method. Horizontal tubing: when the test device was moved to the milking pit and the difference between the device and milk line height is minimized.

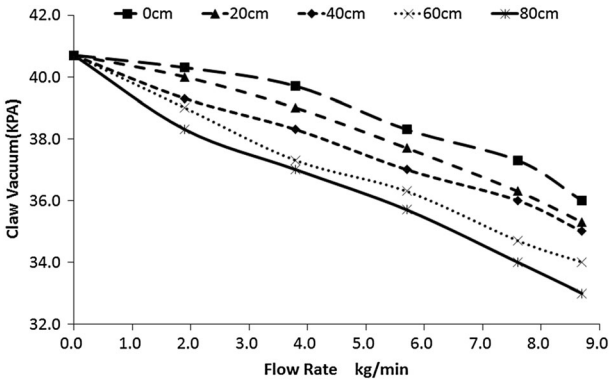

Figure 8 Variations of claw vacuum with milk tube lift height on a lowline system. Effect of lift formation on claw vacuum level at a lowline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 300 cm; aperture diameter, 16 mm.

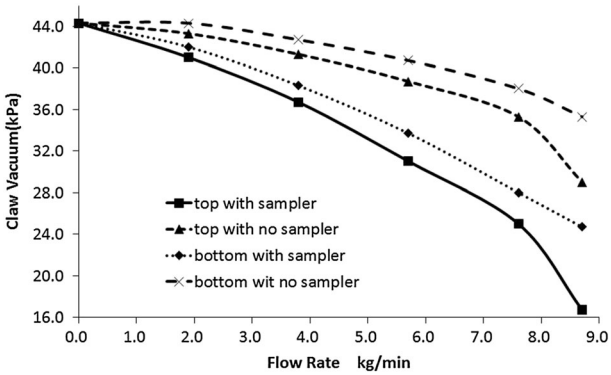

Figure 9 Variation in claw vacuum with claw type and sampler on a lowline system. Effect of claw type and milk meter sampling device installation on claw vacuum level at a lowline system dairy farm. Claw vacuum levels were measured at five flow rates using the flow simulator (0.5, 1.0, 1.5, 2.0, 2.3 gallons/min). Milk tube length, 200 cm; aperture diameter, 16 mm. Top: flow when milk is sucked upwards. Bottom: flow when milk flows from the base of the claw.

health. Accordingly, even different milking systems require a similar teat vacuum pressure during milking. To achieve this, we compared the different pressure settings of the highline and lowline systems.

The claw vacuum levels rapidly decreased below the designated pressure even at minimal flow rates in the highline system, and these decreases became larger as the flow rates increased. In the highline system, exceeding a flow rate of 6.0 kg/min causes the vacuum level to fall below 36.0 kPa. Higher flow rates prevent the rubber liners from providing sufficient teat massaging effects, leading to the risk of damaging the teat orifice. In actual milking, milk yield per minute is determined by the mechanism of oxytocin-induced milk discharge and milker suction. The liner is attached to the teat in a vacuum so when the claw vacuum level becomes low, liner slip is prone to occur and in serious cases it can become detached from the teat altogether. Liner slip therefore tends to occur more frequently when the claw vacuum is 33.3 kPa at a flow rate of 7.6 kg/min. This means that, in the highline system, this flow rate must be seen as increasing the risk of mastitis. Conversely, claw vacuum becomes 42 kPa or above when the flow rate is low, and this high vacuum level can cause damage to the teat orifice. In practice, this is referred to as over-milking in the final stage of the milking process. This issue becomes more conspicuous when fitting an automatic detacher in a highline system.

In the lowline systems, claw vacuum did not decrease as much as in the highline system, even as the flow rate increased, and was maintained at 39.7 kPa at the maximum flow rate of 8.7 kg/min. In areas of low flow rate, the vacuum level is lower and therefore gentler on the teat than in highline milking, and in areas of high flow rate, a higher vacuum level enables greater milk suction (improved milking characteristics) than in highline milking, while also maintaining teat massage pressure. The designated pressure on the lowline system must therefore be lower than on the highline system. When the pressure is set high, a high vacuum is constantly maintained on the teat so there is a greater risk of damaging the teat orifice and for causing mastitis. The lowline system delivers better milking characteristics and is gentler on the teat than the highline system. In lowline milking systems, a milk tube aperture diameter of 22.2 mm prevented decreases in claw vacuum at any of the flow rates and maintained the vacuum at around the designated pressure. We consider that this wide aperture diameter provided a vacuum for milking and more space for the milk to flow within the tube, which resulted in more stable vacuum pressure levels. Using wide-aperture milk tubes (≥18 mm) in the highline system made milking more difficult because the milk conglomerated inside the tube and was unable to rise.

In the dual-series vacuum system, vacuum levels followed a similar curve to those of the lowline system, regardless of the highline configuration. This was attributed to the high 60 kPa vacuum that sucked the milk up the tube more strongly than was possible with a standard highline system (50 kPa). The design of this system was such that the strong vacuum inside the milk tube was decreased inside the claw.

Understanding changes in claw vacuum levels caused by these different milking systems is important in that it allows dairy farmers to determine the optimal designated pressure and to take proper precautions during milking.

Dairy farms use highline, midline and lowline systems. Even milking parlors use various configurations, including swingover parlors that utilize the highline system. Understanding the theory behind each of these systems is therefore essential.

The vacuum inside the milking claw is supplied via milk tubes branching off from the milk line, and these milk tubes also serve to transport the milk to the milk line. Air intake via bleed holes (approx. 10 L/min) causes the milk to clot inside the milk tube, with the subsequent flow of milk to the milk line determined by the difference in respective vacuum levels of the air-fed claw and the milk line before and after clotting. Increasing air intake from the bleed holes adversely affects the milk flow by causing the milk clots to break up. A single milk tube therefore has to perform two roles. Failure to adequately achieve these two functions has an adverse effect on the system's milking properties and causes fluctuations in claw pressure, which in turn increases the risk of mastitis.

In both the lowline and highline systems, claw pressure decreased as milk tube length increased. This was attributed to the fact that greater milk tube length meant that the time the milk spent flowing through the tube in agglomerated form also increased, and this in turn disrupted the vacuum needed for milking, resulting in a drop in claw vacuum levels.

Using a narrower aperture diameter inside the milk tube brought about decreases in claw vacuum levels. The flow of milk clumps through this area was poor and the vacuum required for milking was instantly disrupted, with the end result being a decline in claw vacuum.

Claw vacuum levels decreased in the lowline system milk tubes as the aperture diameter became thinner. The lowline system essentially does not need to suck the milk upwards so the milk flows through the milk tube with the aid of gravity and vacuum suction (i.e. the difference in pressure is caused by the inflow of air via the bleed holes). A wide tube aperture gives rise to a space within the tube that separates the required vacuum and the milk flow for milking, resulting in improved vacuum stability.

Even at identical milk tube lengths and apertures, decreases in claw vacuum levels were slight in the vertical tubing configuration because gravity could be used to assist milk flow.

Even at the same milk tube lengths and apertures, claw vacuum levels differed according to differences in lift. The presence of lift means that the milk has to work against gravity in order to travel up the milk tube. The greater the lift, the longer the milk causes the milk tube to be occluded, thereby disrupting the vacuum required for milking.

In terms of claw type, vacuum levels were lower inside the top-flow milking claw because even a small amount of tubing inside the claw creates a lift tubing configuration in which the milk must be sucked up. Meanwhile, the use of a milk sampler meant that uniformly small amounts of milk were sampled so the milk had to pass through a narrow area, and this area was responsible for decrease in the vacuum level.

Upon using the simulated milking device and analyzing factors that cannot be detected in routine milker inspections, we found that all specifications of the milking unit - including milk tube length and aperture diameter, presence or absence of constrictions in this aperture, use or non-use of an automatic detacher, formation of lifts and the claw type - had a major impact on claw vacuum levels.

The combination of these factors may cause considerable differences in the milking performance of each system, and the simulated milking device should be able to accurately determine actual milking properties. The simulated milking device also allows us to test and investigate improvements (e.g. using thicker milking tubes) to milking system issues identified by the study findings. In terms of preventing mastitis, the device could also be used to diagnose and improve milking system issues before installation at milking parlors, such as diagnosing milking properties and determining pressure settings, component configurations and loss of detacher pressure. With further advances, the device could even be used to assess the quality of developed components.

This study represents the first time that a simulated milking device has been used to analyze the factors that affect milk claw vacuum levels during milking, and demonstrates that it is possible to diagnose the performance of the entire milking system. The study findings suggest that, through the diagnosis of milking system performance, the simulated milking device could enable significant milking system improvements that would reduce the risk of mastitis.

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