Irish Journal of Agricultural and Food Research **50:** 209–221, 2011

Analysis and evaluation of the teat-end vacuum condition in different automatic milking systems

U. Ströbel[1]†, S. Rose-Meierhöfer[1], H. Öz[2], A.-C. Entorf[3], L. Popp[3] and R. Brunsch[1]
[1]*Leibniz Institute for Agricultural Engineering Potsdam-Bornim, Potsdam, Germany*
[2]*Ege University, Ege Vocational Training School, Bornova-Izmir, Turkey*
[3]*Neubrandenburg University of Applied Sciences, Neubrandenburg, Germany*

The number of automatic milking systems (AMSs) installed worldwide shows an increasing trend. In comparison to the preliminary models, new versions employ more sophisticated sensor technology than ever before. The originally developed AMSs were characterised by larger vacuum fluctuations and vacuum reductions than conventional milking systems. The objective of this study was to find out whether this situation still holds or if an improvement has occurred. The vacuum behaviour at the teat end of an artificial teat during simulated milking was measured in a study that involved different AMS types (AMS A, B and C). Each system was tested over a range of flow rates (0.8 to 8.0 L/min). The wet-test method was used and teat-end vacuum behaviour was recorded. At a flow rate of 4.8 L/min, the lowest vacuum fluctuation (6.4 kPa in b-phase) was recorded for AMS A, while the lowest vacuum reduction (3.5 kPa in the b-phase) was obtained for AMS B. AMS C yielded higher values for vacuum reduction and vacuum fluctuation. Consequently, it was concluded that AMS A and B, in terms of construction and operational setting (vacuum level), are more appropriate than AMS C. Nevertheless, high values for vacuum reduction or fluctuation have a negative effect on the teat tissue. Hence, one of the future challenges in milk science is to develop a control system that is able to allow fine adjustments to the vacuum curve at the teat end.

Keywords: Fluctuation; phase; quarter individual; reduction; wet-test-method

---

†Corresponding author: ustroebel@atb-potsdam.de

Introduction

The development of the automatic milking system (AMS) is one of the most important inventions in dairy farming of the 20th century, as has been discussed in the world press (Maris and Roe 2004). Recent data show that, worldwide, over 9000 farms, with approximately 12 000 milking stalls, (Harms 2009) are now equipped with an AMS. The first AMS was marketed in 1992 and sales figures have shown a rapidly increasing trend since 2007 (Halachmi 2009; Harms 2009). This leads to the assumption that the technology and management of AMSs has been improved. Large vacuum reductions and fluctuations were significant problems during the introductory phase. The main requirement expected from any milking system is to obtain the highest milk yield in the shortest time and with the least labour, and this must be achieved without damaging the udder. Udder health is one of the most important factors for successful and sustainable dairy farming. Successful management of milking systems, in the context of the above-mentioned issues, is a substantial key to an economically successful dairy farm.

The objective of the latest scientific studies on milking techniques and automated milking systems is to optimize the aforementioned influential factors. One of the aspects in this regard is to identify the optimal machine settings. There is still some controversy about the optimum teat-end vacuum. Thiel and Mein (1979) showed that while increased machine vacuum led to a higher rate of milk flow this also increased strippings. Thus, the proper adjustment of the teat-end vacuum is very important for the whole milking process. Some researchers have concluded that if the vacuum at the teat end is too high, especially in d-phase, this can lead to damage of the teat tissue. The higher the vacuum under the teat, the stronger is the force which folds the teat cup liner together in c- and d-phases and the teat tissue gets squeezed too much (Hoefelmayr and Maier 1979a). Rasmussen and Madsen (2000) reported that milking at low teat-end vacuum (26 to 30 kPa on average) compared to high teat-end vacuum (33 to 39 kPa) increased machine-on time and the frequency of liner slip. In contrast, milking at high teat-end vacuum reduced machine-on time slightly (Reinemann *et al*. 2001) but increased the number of teat ends open after milking and the time for teat ends to close after milking, and increased teat-end hyperkeratosis (Mein *et al*. 2003). Hyperkeratosis can lead to mastitis over the long-run. The stated vacuum levels in these reports are the mean level at the teat-end vacuum over the whole pulse cycle and not the mean vacuum level of a single pulsation phase. Therefore, the mentioned authors do not indicate, whether a different vacuum is desirable during the suction- and release-phases. To date, both phases could not be adjusted independently so it was not necessary to specify the optimal mean vacuum level for each phase.

On the other hand, low massage pressures at the teat end during the release phase causes vascular congestion in the teat-end tissue, which leads to swelling of the teat ends, a reduction of milking-acceptance by the cow, and often to considerable udder damage with chronic oedema. A high vacuum reduction can lead to an increased frequency of liner slip and to unit fall-off, which disrupts the milking routine (Reinemann 2005). In contrast to the data for very precise adjustments of milking systems, such as individual-cow pulsation settings or milk-flow-based vacuum adjustments, the main settings for milking machines have been known for many years. Subsequently the guidelines specified in ISO (2007a,c), which are regularly updated according to the latest scientific knowledge, were prepared. These guidelines are obligatory for automatic as well as for conventional milking systems. Additionally, the guideline ISO 20966:2007 (ISO 2007d) is obligatory, and was developed, for AMSs only. The implementation of sensor technology in the management of the milking process will make the milking much more efficient and the amount of data per individual animal will also increase. However, the data generated should serve predetermined objectives through the use of decision support systems (Spilke and Fahr 2003), and stimulate the improvement of such systems. Decision support systems should provide the data in a form that the farmer can use efficiently. A further progressive step in milking science will be the collection and use of more and more animal data during the milking process. For example, it may be possible in future to measure the forces on the teat tissue during milking or the diameter of the streak channel during the milking process. Progress in sensor technology makes the evaluation of the teat-end vacuum data easier and faster. The future objective is to develop a milking system that will offer a more optimal and individual-quarter milking process with respect to vacuum behaviour. To meet this objective, fine adjustments of the milking processes will need to be much more exact than those available at the present time.

Most AMSs use independent teat cups that are usually linked to a milk meter or recording jar via a single long milk tube (Svennersten-Sjaunja, Berglund and Pettersson 2000). Rose, Brunsch and Huschke (2006) found that the internal diameter of the milk tube affects the teat-end vacuum, especially in milking systems without a claw. While vacuum levels at the milk receiver and the pulsator settings in AMSs are similar to those used in conventional milking systems (Hillerton 1997) the teat-end vacuum levels may differ. O'Callaghan and Berry (2008) tested a conventional cluster system and a single teat-cup unit and found that the single teat-cup unit, with light teat cups, had a longer milking time and lower peak and average milk-flow rates compared with the conventional-cluster system. Furthermore, they found that while the vacuum curve profile of the conventional machine and the single teat-cup configurations were similar, the vacuum reduction at the teat end in the b-phase of pulsation was higher with the single teat cups. Hamann (1987) concluded that mastitis can be caused through suboptimal adjustment of the milking process such as failure in pulsation and suboptimal teat-end vacuum. This applies to all kinds of milking system. The main reason for suboptimal teat-end vacuum conditions are, as mentioned, milk tubes that are too long with diameters that are too small, especially in AMSs. On the other hand, the internal diameter of the milk tubes in AMSs cannot be made larger since the handling of four large milk tubes could be very difficult. Thus, a control system for the teat-end vacuum needs to be included in AMS equipment in the future and this could help to solve the problems mentioned above.

By measuring the vacuum reduction and fluctuation in AMSs, a prediction can be made about the likely impact on the teat tissue. A change in system settings can often improve the impact on the teat ends. Therefore, three AMSs, that are the most widely purchased models worldwide, were studied to evaluate their vacuum reduction and fluctuation characteristics.

Materials and Methods

The details of the different AMS types used and the system settings are given in Table 1.

Table 1. Technical details of the three automatic milking systems investigated

	Automatic milking system		
	A	B	C
Year of manufacture	2008	2008	2006
Machine vacuum (kPa)	47	44	44
Flow rate (L/min)	0.8 to 8	0.8 to 8	2.0 to 8
Test liquid	milk	milk	artificial milk
Pulsation ratio	65/35	65/35	60/40
Pulsation rate (cycles/min)	60	60	60
Pulsation type	Alternating	Alternating with individual quarter regulation	Alternating
Construction of milking unit	Individual quarter	Modular	Individual quarter
Milk tube length from teat cup to the claw (mm)	2000	4600	2500
Internal diameter of the milk tube at the connection to the teat cup (mm)	12	12	11

Test setup

Vacuum measurements were conducted, using the wet-test method and artificial teats (ISO 2007c). Milk, or artificial milk, at room temperature was used to simulate the effects of milk flow and the flow rate employed ranged between 0.8 and 8.0 L/min. Four flow meters (Parker Hannifin Corporation, Cleveland, USA) installed on a board were used to simulate flow rate. Each flow meter allowed adjusting the flow rate between 0.0 and 2.0 L/min with a measuring accuracy of ±2%. Each AMS was operated in normal milking mode. The robotic arm for attaching the teat cups was used only with AMS B because its milking unit was of a modular construction. The teat cups of AMS A and AMS C were attached to the artificial teats by hand. This is possible in AMSs with individual-quarter guided milk tubes. The vacuum was measured using a Bovi Press measuring system (A & R Trading GmbH, Echem, Germany) that sampled at > 300 Hz and with an accuracy of ±0.1 kPa; a measuring accuracy of ±0.6 kPa is required as defined in (ISO 2007c). The vacuum was recorded, simultaneously, over 7 pulsation cycles for each measurement at the teat end of the artificial teats (ISO 2007c), in the pulsation chamber, and in the machine vacuum line. Sensors were connected by small tubes or T-pieces to the teat end, to the short pulse tube, and to the machine vacuum line. The T-pieces can be used for connecting the pressure sensor with the tube inside. From the data recorded, the mean vacuum for the b-phase and the d-phase, and the vacuum fluctuation for these two phases were calculated for each pulsation cycle.

Another difference between the three systems was that the "milking unit" of AMS B was constructed as a module, described by Rose (2005) and Schön *et al*. (2000) whereas AMS A and AMS C each had individually guided milk tubes. The teat cups of each system were constructed with an air-inlet at the end of each teat cup that allows air ingress into the milk tube. All three systems employ alternating pulsation, which reduces vacuum fluctuation compared to simultaneous pulsation in an individual-quarter milking system (Ströbel *et al*. 2009). Furthermore, all three systems were equipped with a frequency controlled vacuum pump.

Statistical analysis

The data recorded were used to calculate the mean vacuum in the b-phase and in the d-phase of the pulsation cycle; the percent share of the pulsation cycle was also calculated for each of these phases. For each repetition at each flow rate the data from 7 selected subsequent pulsation cycles were considered and the vacuum fluctuation (*vf*) for each phase was calculated as follows (ISO 1996):

$$vf_{phase} = \frac{1}{n} \times \sum_{i=1}^{n} (p\max_i - p\min_i)$$

with i=pulsation cycle, $p$max=maximum vacuum per pulsation cycle, $p$min=minimum vacuum per pulsation cycle and n=number of subsequent pulsation cycles.

The determination of pulsation phases was carried out using an SAS macro according to the formulae presented in ISO (2007b,c). Evaluation of effects on vacuum reduction at the teat end was made using parametric tests for a linear model (Proc MIXED; SAS 2010). An adjustment for multiple comparison tests between factor levels was accomplished using the SIMULATE option.

The linear model used was

$$y_{ij}=\mu+\alpha_i+\beta x=(\alpha\beta)_i x+e_{ij}$$

where,

y_{ij} – vacuum reduction or vacuum fluctuation,
μ – general mean,
α_i – (fixed) effect of ith milking system (i=1,...,3),
β – (fixed) effect of covariate x (flow rate),
$(\alpha\beta)_i$ – (fixed) effect of interaction between ith milking system and covariate x,
e_{ij} – independent normally distributed residual.

Milking systems 1 through 3 refer to AMS A, AMS B and AMS C. Three repetitions per quarter were available for AMS A, while 2 repetitions per quarter were made for AMS B and AMS C. Total sample size over all flow rates was 157, 158 and 144 for AMS A, AMS B and AMS C, respectively.

Results

Comparison of pulse cycles

The teat-end vacuum, pulsation chamber vacuum and machine vacuum measured over one pulse cycle for AMS are plotted in Figure 1a,b for flow rates of 2.0 L/min and 4.8 L/min. The corresponding data for AMS B are in Figure 1c,d and those for AMS C are in Figure 1e,f. Each AMS had a characteristic pulsation chamber curve. In the case of AMS A and B the combined duration of the a- and b-phases was almost the same, *ca.* 650 ms, while the corresponding duration for AMS C was *ca*. 600 ms. However, the shape of the pulsation curve was particular to each AMS type. The profile of the pulsation-chamber vacuum in AMS A exhibited a nearly vertical line at the beginning of the c-phase; the vacuum decreased abruptly, so the liner closed very quickly until the vacuum reached 10 kPa, after which the closing process slowed down. In the case of both AMS B and AMS C the vacuum level declined at a constant rate during the c-phase and, consequently, the liner closed at a more constant rate. All AMSs exhibited a low vacuum reduction at teat end during the b-phase and a much larger reduction during the d-phase.

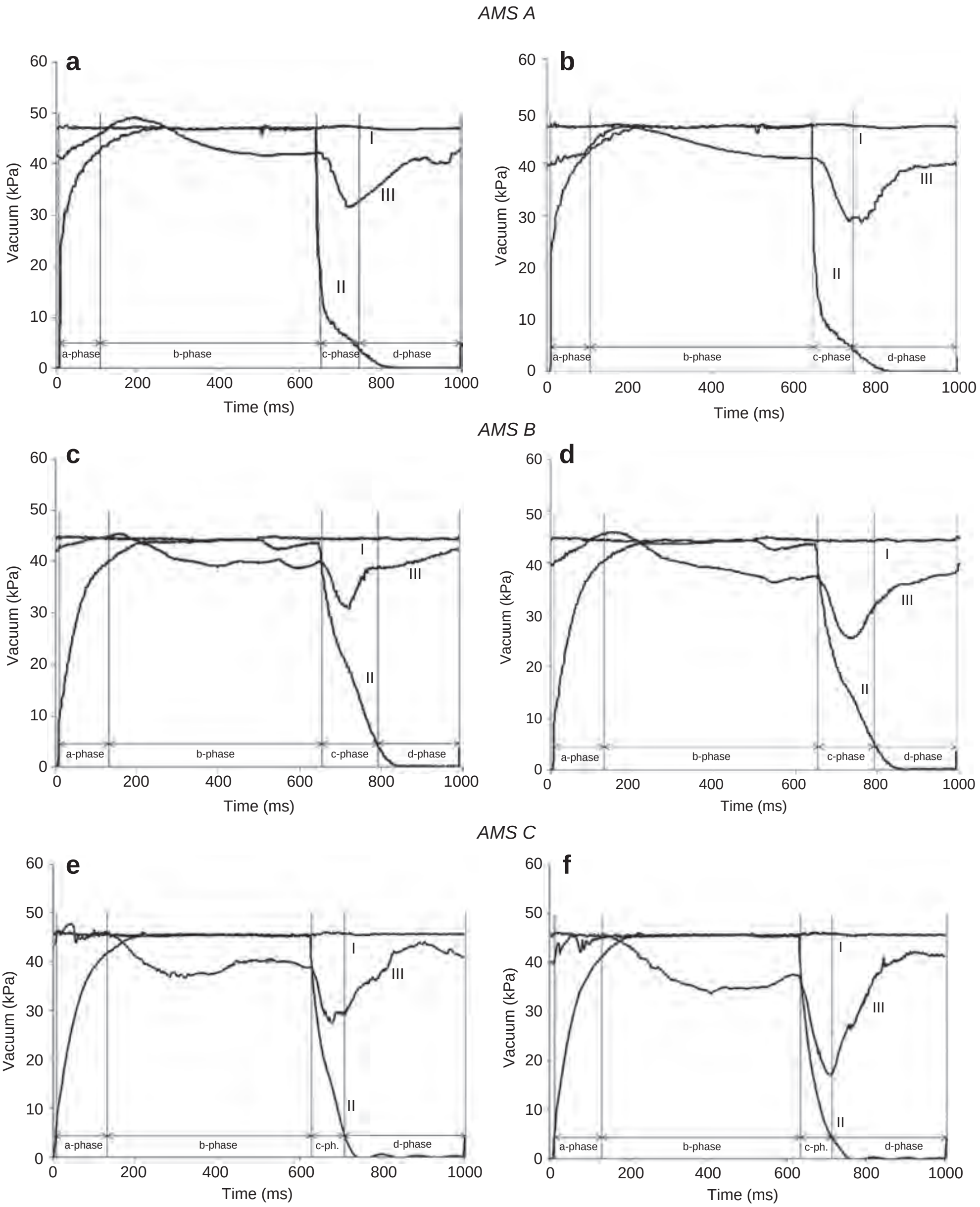

Figure 1. Vacuum changes as a function of time for machine vacuum (I), pulsation chamber vacuum (II) and teat-end vacuum (III) for AMS A, AMS B and AMS C at flow rates of 2.0 L/min (panels on the left) and 4.8 L/min (panels on the right), as measured at the rear left quarter.

A difference between the machine vacuum and the teat-end vacuum, called vacuum reduction, was measurable in all milking systems and was observed at all flow rates examined in this study. The vacuum curves for the teat-end vacuum were similar for AMS A and B with a low vacuum reduction. The reductions for AMS C were somewhat higher. The teat-end vacuum with AMS C declined to a minimum of 20 kPa during the c-phase at a flow rate of 4.8 L/min. During the b-phase the reduction in teat-end vacuum with AMS C was not as flat as with the other two systems. For all three systems vacuum reductions in b-, c- and d-phases were greater at the higher flow (4.8 L/min; Figure 1). Increased milk flow led to greater vacuum reductions over all phases with AMS C than with AMS A or B.

Vacuum reduction and fluctuation

The results of the wet-test for the effect AMS type, flow rate and their interaction for vacuum reduction and fluctuation in the b- and d-phases are given in Table 2. The F test showed that both flow rate and the interaction between flow rate and milking system had significant effects on vacuum reduction and vacuum fluctuation ($P < 0.0001$) in both phases. A significant effect of the milking system was only found for the vacuum reduction in d-phase and for the vacuum fluctuation in b-phase. The significant effects of flow rate show that increasing flow rate increased both the vacuum reduction and fluctuations. Further, the significant interaction between flow rate and milking system indicates that the slopes are different among the three investigated AMSs. For all three systems the teat-end vacuum reductions and fluctuations increased as the flow rate was increased.

At a flow rate of 4.8 L/min, the values for average vacuum in the liner during the b-phase were 42.0, 40.5 and 37.5 kPa for AMS A, AMS B and AMS C, respectively. Thus, the corresponding values for the mean vacuum reduction were 5.0, 3.5 and 6.5 kPa, respectively. As for the b-phase, the average liner vacuum in the d-phase differed slightly among the systems; it ranged between 36.0 and 37.1 kPa at a flow rate of 4.8 L/min. Thus, at a flow rate of 4.8 L/min, the vacuum reductions were 9.9, 7.9, and 8.0 kPa for AMS A, AMS B and AMS C, respectively.

In the b-phase, AMS B exhibited the lowest slope for the regression of vacuum reduction on flow rate among the tested AMSs, leading to the overall lowest vacuum reduction in that phase. AMS C on the other hand showed a response to flow rate that was almost three times greater. The effect of flow rate on vacuum reduction in AMS A was roughly between AMS B and AMS C (Figure 2).

AMS C showed the lowest vacuum reduction in the d-phase for all flow rates below 4.5 L/min. At higher flow rates AMS B exhibited the lowest vacuum reduction in that phase. With the exception of flow rates below 1.5 L/min, the highest vacuum reduction in the d-phase was always associated with AMS A (Figure 3).

In all systems tested the vacuum fluctuation increased as the flow rate increased (Table 2). This was true for both the b-phase and the d-phase. In AMS A vacuum fluctuations in the b-phase were lowest among the systems tested, with only a marginal slope of the estimated regression line (Table 2). AMS B showed higher vacuum fluctuations in the b-phase, and the value increased almost three times as much as for AMS A with increasing flow rate. In contrast, the effect of flow rate on vacuum fluctuations in the b-phase for AMS C was about 9 times as high as that in AMS A. Moreover, the slope of the regression line in b-phase (effect

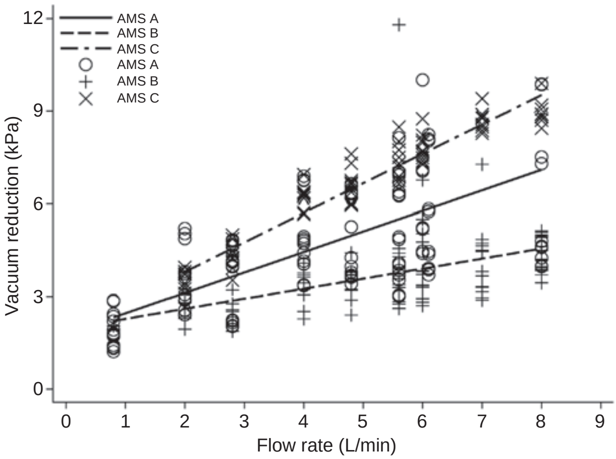

Figure 2. Vacuum reduction at the teat end in b-phase as a function of flow rate (straight lines are the estimated regression lines).

of flow×milking system in b-phase) of AMS C was significantly higher than for AMS A or B ($P<0.0001$). For the vacuum fluctuations in d-phase it was found that the slope of vacuum fluctuation on flow rate for AMS C was also highest, with an increase in fluctuations of about 2.7 kPa per 1 L/min increase in flow rate (Table 2). On the contrary, no significant influence of flow rate on the vacuum fluctuation in the d-phase was found for AMS B. The effect of flow rate on vacuum fluctuation for AMS A in the d-phase was less than one-third of the corresponding effect for AMS C. The effect of flow rate on vacuum fluctuation with AMS C was higher in d-phase than in the b-phase, although such differences could not be formally tested with the statistical model employed. Calculations, from the linear

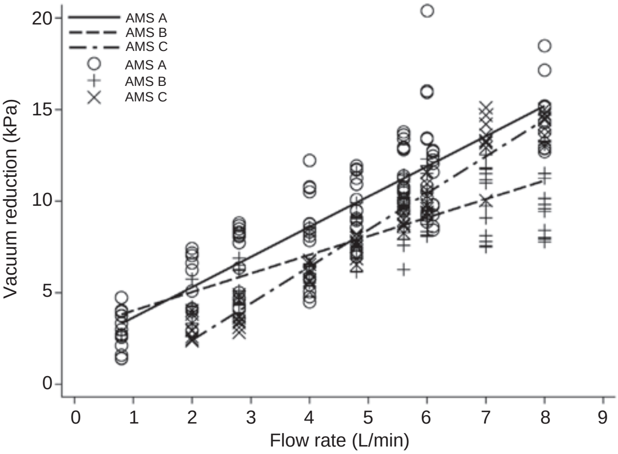

Figure 3. Vacuum reduction at the teat end in d-phase as a function of flow rate (straight lines are the estimated regression lines).

Table 2. Estimates (±s.e.) of least squares means[†], and coefficients of regression on flow rate, for vacuum reduction and vacuum fluctuation during b- and d-phases of the pulsation cycle for three automatic milking systems

Effect	Vacuum reduction (kPa) in		Vacuum fluctuation (kPa) in	
	b-phase	d-phase	b-phase	d-phase
Milking system				
AMS A	4.98±0.096	9.92±0.131	6.41±0.110	9.24±0.204
AMS B	3.52±0.096	7.88±0.131	8.47±0.110	5.69±0.205
AMS C	6.47±0.096	8.03±0.131	12.63±0.110	19.23±0.204
Regression on flow rate for				
AMS A	0.66±0.044	1.65±0.061	0.14±0.051	0.78±0.094
AMS B	0.33±0.050	1.02±0.068	0.36±0.057	0.14±0.106
AMS C	0.95±0.050	2.01±0.068	1.27±0.057	2.70±0.106
F test for heterogeneity	<0.0001	<0.0001	<0.0001	<0.0001

[†] At a flow rate of 4.8 L/min.

model, show that the vacuum fluctuation for AMS C was 16.7 kPa in the b-phase and about 27.9 kPa in d-phase at the highest flow rate (8.0 L/min).

Discussion

Comparison of pulse cycles

The results of this study showed differences in the mechanical behaviour of the pulsator valves of each AMS, especially in the c-phase. This had an effect on the characteristic pulsation curves of each AMS (Figure 1). O'Callaghan and Berry (2008) investigated a self-developed individual-quarter milking system (IQS) in a parlour with a high milk line. In that study the machine vacuum was 50 kPa compared with 44 to 47 for the systems tested in the present study Thus, the mean vacuum reductions with the IQS in that study can be compared with the mean reductions for the AMSs in this study at flow rates of 4 and 6.2 L/min. The AMSs in the present study had substantially smaller vacuum reductions in b- and d-phase. Thus, in the b-phase the IQS had a reduction of 17.0 kPa at a flow rate of 4.0 L/min compared with a mean value of 4.4 kPa for the three systems tested in the present study. Furthermore, the IQS, at a flow rate of 4.0 L/min in d-phase, showed a vacuum reduction of 25.0 kPa compared with a mean reduction of 7.2 kPa for the systems tested in this study. The given relationship was proportionally higher at higher flow rates for all four of these milking systems. But the vacuum reduction should be on a more constant level across the values for flow rate. Here again the situation in the AMSs seems better. The main reason for the greater reductions with the IQS used by O'Callaghan and Berry (2008) was probably the fact that they used a high milk-line installation. Furthermore, the milk line used with the IQS had a smaller internal diameter (9.0 mm) than any of the systems used in the present study (Table 1); also AMS B had an electronic pulsation steering system, individually controlled for each udder quarter. It is recommended in ISO 6690:2007 (ISO 2007) that the short milk tubes should have a minimum diameter of 10 mm.

Vacuum reduction

O'Callaghan (2004) studied the effects of milking unit design on vacuum variation during simulated milking and found that increasing the bore of the long milk tube resulted in a significant increase in teat-end vacuum in the b-phase in an experiment with several milk cluster types. Rose *et al.* (2006) reported that in an IQS the internal diameter of the milk tubes influences the teat-end vacuum in a comparison involving 4 frequently-sold conventional milking cluster (MC) systems in a low-line installation and one individual quarter system. Rose *et al.* (2006) also found that mean vacuum reduction (per pulse cycle), for four MC systems, was approximately 9.8 kPa at a flow rate of 8.0 L/min and 5.3 kPa for the IQS with four long milk tubes (16 mm internal diameter). The three AMSs in the present study showed mean vacuum reductions that were lower than 10.0 kPa for flow rates of 8.0 L/min (mean of three AMSs). This indicates that modern AMSs have reached a level of vacuum reduction in b-phase that is similar to that of modern MC systems equipped with large claws and with a low-level vacuum line. Additionally, Rose-Meierhöfer *et al.* (2010) found, in on-farm milking-time tests, a vacuum reduction of 15.0 kPa at 8.0 L/min flow rate for a conventional MC system with a claw volume of 300 ml at a machine vacuum of 42 kPa. Thus, all three AMSs showed values between the best and the worst reported values for MC systems. The study of Rose *et al.* (2006) confirms that individual-quarter systems with a large internal diameter (16 mm) of the four long milk tubes can lead to vacuum reductions that are on the same low level as with the best modern MC systems.

There are two main reasons for using tubes with internal diameters of 11 or 12 mm instead of 16 mm. The handling of such wide tubes is difficult and thus they should be avoided since short milk tubes with a large internal diameter also give low vacuum reductions in b- and d-phases. But higher vacuum reductions in the d-phase, where the teat should be released from suction, are required to maintain good teat condition. Hamann *et al.* (2001) confirmed this by showing that a milking system with the application of positive pressure (that is similar to high vacuum reduction) in the d-phase significantly reduced teat-end diameter and lowered thickness values as compared to the conventional milking system with relatively high d-phase vacuum. Therefore it is desirable to achieve a lower vacuum compared to the currently achieved vacuum levels in the d-phase with all three tested AMSs across all flow rates.

Overall, the average vacuum reduction in all tested AMSs was almost at the same low level as in modern systems involving milking clusters, and the lead of the best milking-cluster based systems has become smaller; thus the performance of AMS B in the present study is almost the same as that of the best MC design in a conventional low-line milking system. It is probable that the results for AMS B are only possible because the system is equipped with an individual-quarter control system for the pulsation at each teat. This individual-quarter control system reacts to the measured process data from the milking system and the vacuum application at each teat is indirectly adjustable, but in a not very precise way, by changing the programmed pulsation regime, which influences the mean vacuum level of each pulsation phase. Many of the issues mentioned above coincide with the statement of Rasmussen *et al.* (2006) that many of the problems, such as elevated bacterial counts, elevated cell counts and increased freezing point in milk, from AMSs have been solved and only the high free fatty level remains a problem. However, the free fatty acids are more likely to arise from the effect of the air-inlet and the number of milkings per day rather than the average vacuum conditions at the teat end. It can be argued that the improvement of teat-end vacuum conditions in

AMSs over recent years is one of the reasons why many of the original problems with AMS equipment have been eliminated. However, some issues still remain to be solved. The combination of a higher vacuum in the b-phase with a low vacuum in d-phase would help minimize the disadvantages of milking at high or low teat-end vacuum. An adjustment of teat-end vacuum in the suction and release phases separately is not generally available in all milking systems at present although some technical solutions for different vacuum levels among the phases are already available, such as in the Biomilker (Hoefelmayr and Maier 1979b). The Biomilker technology, or an electronic vacuum-regulation system for the teat-end vacuum conditions adjustable for each phase of the pulsation cycle, could be the solution for all kinds of individual-quarter milking systems and in particular for AMSs. In some cases wide-bore tapered liners and simultaneous pulsation could also help to reduce the d-phase vacuum.

Vacuum fluctuation

The vacuum fluctuations measured during the b-phase, at a flow rate of 8.0 L/min, were highest for AMS C (16 kPa) and lowest for AMS A (6.5 kPa). These results are consistent with other studies in which high fluctuations and stability problems with the vacuum were observed in a conventional system with long milk tubes (Rasmussen *et al.* 2006). In 2002, Bjerring and Rasmussen (2002) found that the vacuum fluctuations at the teat end are larger in AMSs than in conventional milking systems. They mentioned that blocking of the air intake still increases the vacuum fluctuation and higher air intake leads to a higher concentration of free fatty acids in the milk. So higher air intake as realized at the moment in AMS would not be good for the free fatty acid level in milk. In the b-phase, low fluctuations are desirable but high fluctuation in the d-phase do not indicate poor vacuum conditions at the teat end, because the desirable high vacuum reduction in that phase also causes a high fluctuation. Rasmussen *et al.* (2006) reported a significant interaction between milking phase and air intake for the AMS models used in that study. Moreover, it was found that the AMS model and water flow rate were the most significant variables (explained 74% of the variation in vacuum fluctuations at the teat end). In the present study a significant interaction between AMS type and flow rate was also found in almost all cases. Some results of the former study of Rasmussen *et al.* (2006) are that vacuum fluctuations during simulated water-flow-based milking were 20.5, 23.3 and 35.5 kPa, respectively, for three different models of AMS, at a flow rate of 8.0 L/min. All these were calculated over the entire pulse cycle. In comparison, the mean fluctuations of the three AMSs tested in the present study, in the d-phase, were approximately 15.0 kPa at 8.0 L/min. While it is recognised that measurement over the entire pulse cycle yields higher fluctuations than when measured only in the d-phase, it can be stated that current AMS models have similar or lower vacuum fluctuations compared with earlier models, such as those used by Rasmussen *et al.* (2006).

Öz *et al.* (2010) reported vacuum fluctuations of 4.0 and 5.0 kPa in the b-phase for a conventional milking-cluster system, with a claw volume of 160 mL and at flow rates of 0.8 and 6.0 L/min. AMS A, which had the lowest fluctuations in the b-phase, had vacuum fluctuations of 6.0 and 7.0 kPa for flow rates of 0.8 and 6.0 L/min. The other models tested, and especially AMS C, had far higher fluctuations in the b-phase under these conditions. Since vacuum fluctuations can have a negative impact on teat tissue (Hoefelmayr and Maier 1979a) the control of vacuum fluctuation during the b-phase is an important issue for future research. A high vacuum reduction in the d-phase is desirable and hence only the figure for b-phase fluctuation should be used for the quality evaluation of milking systems.

In summary, it can be stated that the vacuum fluctuations in the newer models of AMSs tested in this study did not show higher values as reported in studies on older AMS models. The measured fluctuations are lower or have been steady. Further, it can be stated that the vacuum fluctuations in b-phase for the tested AMS models are considerably higher in comparison to conventional milking systems with modern milking clusters. One reason for this is the necessity for relatively long, individually guided milk tubes in AMSs, which yield many advantages to be considered against the negative impact on vacuum fluctuation. In all the tested AMSs the individually guided milk tubes are longer than 2000 mm (Table 1).

Conclusions

Vacuum reductions were on a similar level but vacuum fluctuations were considerably higher in the tested AMSs in comparison to modern conventional systems with milking clusters with a large claw volume in a low-line installation. None of the AMSs tested had a vacuum reduction in the d-phase that is high enough to protect the teat tissue adequately and, thus, further research is necessary to develop a vacuum reduction and fluctuation control system for the teat-end vacuum in individual-quarter milking systems.

Acknowledgements

The authors would like to thank the three AMS manufacturers and their authorised dealers for the provision of their automatic milking systems. We also would like to thank the farmers, who owned the milking systems, for their kind help throughout the measuring process for this study. The study was funded by the Federal Agency for Agriculture and Nutrition (BLE) as a management agency for the Federal Ministry of Food, Agriculture and Consumer Protection (BMELV).

References

Bjerring, M. and Rasmussen, M.D. 2002. Vacuum fluctuations in the liner during automatic milking. *Proceedings of the First North American Conference on robotic milking, Toronto, Canada,* pages 64–66.

Halachmi, I. 2009. Simulating the hierarchical order and cow queue length in an automatic milking system. *Biosystems Engineering* **102:** 453–460.

Hamann, J. 1987. The role of machine factors in the aetiology and pathogenesis of mastitis. *Hohenheimer Arbeiten. Research on Milk Production, Stuttgart, Germany*, pages 22–56.

Hamann, J., Bronzo, V., Moroni, P., Casula, A. and Zecconi, A. 2001. Conventional and positive pressure pulsation effects on bovine teats and on immunological components of different milk fractions. *Milchwissenschaft* **56:** 423–427.

Harms, J. 2009. Automatisches Melken – Stand der Technik und Entwicklungstendenzen. *ART-Schriftenreihe* **9:** 105–113.

Hillerton, J.E. 1997. Milking equipment for robotic milking. *Computers and Electronics in Agriculture* **17:** 41–51.

Hoefelmayr, T. and Maier, J. 1979a. Vom klassischen Zweiraumbecher und seinen Funktionsmängeln. *Milchpraxis* **17:** 62–64.

Hoefelmayr, T. and Maier, J. 1979b. So arbeitet der Bio-Milker. *Milchpraxis* **17:** 65.

[ISO] International Organization for Standardization. 1996. ISO 6690:1996 Milking machine installations – Mechanical tests.

[ISO] International Organization for Standardization. 2007a. ISO 3918:2007 Milking machine installations – Vocabulary.

[ISO] International Organization for Standardization. 2007b. ISO 5707:2007 Milking machine installations – Construction and performance.

[ISO] International Organization for Standardization. 2007c. ISO 6690:2007 Milking machine installations – Mechanical tests.

[ISO] International Organization for Standardization. 2007d. ISO 20966:2007 Automatic milking installations – Requirements and testing.

Maris, U. and Roe, K. 2004. Milk in the news. In: "*Automatic Milking – a Better Understanding*" (eds. A. Meijering, H. Hogeveen and C.J.A.M. de Koning), Wageningen Academic Publishers, Wageningen, Netherlands, pages 41–45.

Mein, G.A., Williams, D.M. and Reinemann, D.J. 2003. Effects of milking on teat-end hyperkeratosis: 1. Mechanical forces applied by the teatcup liner and responses of the teat. *Proceedings of the 42nd Annual Meeting of the National Mastitis Council, Fort Worth*, *USA,* pages 114–123.

O'Callaghan, E.J. 2004. Effects of the design of a milking unit in vacuum variations during simulated milking. *Irish Journal of Agricultural and Food Research* **43:** 237–245.

O'Callaghan, E.J. and Berry, D. 2008. A note on the design and testing of single teat cups for automatic milking systems. *Irish Journal of Agricultural and Food Research* **47:** 205–209.

Öz, H., Rose-Meierhöfer, S., Bilgen, H. and Brunsch, R. 2010. Determination of vacuum characteristics in conventional and single tube milking systems using the wet-test-method. *Milk Science International* **65:** 238–241.

Rasmussen, M.D. and Madsen, N.P. 2000. Effects of Milkline Vacuum, Pulsator Airline Vacuum, and Cluster Weight on Milk Yield, Teat Condition, and Udder Health. *Journal of Dairy Science* **83:** 77–84.

Rasmussen, M.D., Wiking, L., Bjerring, M. and Larsen, H.C. 2006. Influence of air intake on the concentration of free fatty acids and vacuum fluctuations during automatic milking. *Journal of Dairy Science* **89:** 4596–4605.

Reinemann, D.J., Davis, M.A., Costa, D. and Rodriguez, A.C. 2001. Effects of milking vacuum on milking performance and teat condition. *Proceedings of the 2nd International Symposium on Mastitis and Milk Quality, Vancouver*, *Canada,* pages 357–361.

Reinemann, D.J. 2005. The history of vacuum regulation technology. *Proceedings, Annual Meeting of the National Mastitis Council, 16–19 January 2005, Orlando*, *USA*, pages 124–132.

Rose, S. 2005. Untersuchung mechanischer Belastungen am Euter bei verschiedenen Melksystemen. Dissertation. *Forschungsbericht Agrartechnik des Verbandes deutscher Ingenieure* Nr. 436, Eigenverlag, Berlin.

Rose, S., Brunsch, R. and Huschke, W. 2006. Single tube guiding in conventional milking parlours. *Proceedings of the XVI World Congress of the International Commission of Agricultural Engineering, Bonn, Germany*, pages 455–456.

Rose-Meierhöfer, S., Hoffmann, G., Öz, H., Ströbel, U. and Ammon, C. 2010. Milking-time tests in conventional and quarter-individual milking systems. *Landbauforschung – vTI Agriculture and Forestry Research* **60:** 11–15.

SAS, 2010. Version 9.2, SAS Institute Inc., Cary, NC, USA.

Schön, H., Wendel, G., Pirkelmann, H., Artmann, R., van Hoven, F., Stumpenhausen, J., van Leeuwen, M., Hagting, J., Osthues, U., Bruckmaier, R.M. and Meyer, H.D. 2000. Automatische Melksysteme. *Kuratorium für Technik und Bauwesen in der Landwirtschaft e. V. (KTBL-Schrift)* Nr. 395.

Spilke, J. and Fahr, R. 2003. Decision support under the conditions of automatic milking systems using mixed linear models as part of a precision dairy farming concept. *Proceedings of the European Federation for Information Technology in Agriculture Conference, Debrecen, Hungary*, pages 780–785.

Ströbel, U., Rose-Meierhöfer, S., Ammon, C. and Brunsch, R. 2009. Quarter individual milking with Multilactor® in milking parlours. *Landtechnik* **64:** 106–108.

Svennersten-Sjaunja, K., Berglund, I. and Pettersson, G. 2000. The milking process in an automatic milking system, evaluation of milk yield, teat condition and udder health. *In: "Robotic Milking"* (eds. H. Hogeveen and A. Meijering), Wageningen Academic Publishers, Wageningen, Netherlands, pages 277–288.

Thiel, C.C. and Mein, G.A. 1979. Action of the cluster during milking. In: "*Machine Milking, Technical Bulletin 1*" (eds. C.C. Thiel and F.H. Dodd), National Institute for Research in Dairying, Reading, UK, pages 116–155.

Received 9 June 2010