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Development and Experimental Use of Measurement Technique for Instantaneous Milk Flow Rate through the Cow's Streak Canal

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PREFACE

This report is a survey of the different methods used at the Department of Agricultural Engineering at the Swedish University of Agricultural Sciences (SLU) for measuring the instantaneous milk flow rate.

I wish to express my deepest appreciation to Michael Mayntz, at the Department of Agricultural Engineering (SLU) for important contributions, help and guidance. He has been my tutor for this special task since January 1989. He endured all my excuses for delays concerning this report with patience and understanding.

I would like to thank Alfredo de Toro who taught me how to write computer programs in order to draw different figures used in this paper, and also for allowing me to borrow the computer.

A special acknowledgment and my grateful thanks to Alfa Laval at Tumba are in order since it was their financial support that enabled me to complete this paper within a reasonable space of time.

Uppsala March 1990 HUIBERT HENDERIKUS OOSTRA

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1 SUMMARY

The equipment described in this paper is being used in an introductory research program at the Department Of Agricultural Engineering, Swedish University of Agricultural Sciences (SLU). A measuring method had to be developed since there was nothing directly available that satisfied our needs.

New and better techniques were gradually developed as the research program progressed. An improved equipment design was normally used directly after it had been tested in the laboratory.

Two principally dissimilar measurement techniques were used, a Doppler device and a orifice measuring device.

The Doppler device is described in sections 5.1, 5.2 and 5.3. Three different versions were developed. Firstly a Doppler device directly attached to the cow's teat, secondly a contact-free Doppler device and thirdly a shunted contact-free Doppler device.

In sections 5.4, 5.5, 5.6, 5.7 and 5.8 the various versions of the orifice measurement system are described.

Three different experimental teat cups are listed in this paper. One was used in the non contact-free measuring system, i.e. the Doppler device was directly attached to the teat. The other two teat cups made it possible to apply a contact-free measuring method. The two latter cups were basically equivalent to one another. A regulation system needed when using contact-free milk flow rate measuring techniques is described in Section 5.2.3.

Other equipment not strictly used for measuring milk flow rate has also been developed. These are devices not actually used for milk flow rate measurements but are of the utmost importance for accurate measurements.

The description and explanation of the different measuring techniques is preceded by a short review of literature dealing with the physiology of the cow's teat. Views and research results of various scientists are also listed.

2 INTRODUCTION

This essay is a documentation of the milk flow measuring techniques used in a research program at the Department of Agricultural Engineering, Swedish University of Agricultural Sciences during the period 1 June 1985 to 1 June 1989. Although the research program concerns many different technical problems, such as automatic pressure control, milk flow measurement, data evaluation, etc., its primary goal is to understand how the mechanism of the cow teat works. In addition, the program deals with the reactions of the teat to stress applied by the milking technique. With the equipment developed at this institute it was possible to continue the research where the Department of Agricultural Engineering at Cornell University, USA had stopped in 1981. Over the years we have been improving the equipment stepwise. The equipment developed from being simple but efficient to a very sophisticated computer-controlled system with many specific characters. All these improvements are based upon our experiences during these four years of experimentation.

This essay will not deal with the computer and the software used to measure the milk flow, and neither does it touch upon any of the other peripheral equipment, such as the device for measuring pressure inside the experimental teat cup, the valve that regulated this pressure together with the computer, the different programs used for regulation, calibration, etc. The data evaluation is also beyond the scope of this paper. In the present context the discussion deals only with the theoretical sides of the flow measurement methods used and their practical application.

Beside a strictly technical explanation of the different flow measurement techniques used, a short introduction is given of the complicated world of the cow teat's physiology, because measuring never is a primary goal in itself.

The broad scope of the research program was to obtain better understanding of the mechanisms that control the ability of the streak canal sphincter to release milk or to seal. The best method to investigate this complicated issue is to use some form of "muscle activity meter". This method is unfortunately not feasible because the changes in electrical potential due to the activity of the smooth muscles of the teat are too small in comparison with those emitted by other muscles. An indirect method is to study the instantaneous milk flow rate and then to interpret the changes of flow rate in terms of muscle activity and muscle state.

This requires a sophisticated measuring technique. A method that shows the total milk yield from different intervals is not sufficient. The changes in muscle activity in the teat sphincter can be rather abrupt and of a magnitude varying from almost undetectable to major shrinkage of the teat. Therefore, the data should have a high resolution. To obtain this quality, it must be possible to measure several times during a short period. This is only possible if a reliable measurement probe is combined with appropriate hard- and software.

The measuring probe must fulfil a number of requirements. Firstly, it must provide the computer with reliable data so that a relevant evaluation can be based upon them; secondly, it must be solidly built and capable of withstanding the environment in which the device is used. Milk can lead to deposits even on smooth surfaces. A deposit on the measuring probe may change the flow resistance and thereby the characteristic measured. Therefore, the device must be easily cleaned. Although not a major requirement, it is convenient if the device is transparent, e.g. for optical observation of gas bubbles or foam. Too many gas bubbles can jeopardize the entire measurement.

3 THE IMPORTANCE OF MEASURING THE INSTANTANEOUS MILK FLOW RATE

A simple calculation shows that the milk flow rate through a cow's streak canal is, on average, between 16 and 30 ml/s during a vacuum phase. This amount of milk must be extracted from the udder in a biologically appropriate manner. Although it is almost 90 years since the present technique was invented, there have been only moderate changes, for instance changes in appearance of clusters, liner collars, milk claws, etc. The conventional milking method affects the teats with a hard and a one-sided strain. The teats are tied off at the teat base and the smooth muscles are prevented in their natural activity (Mayntz, M. 1984; Mayntz, M. 1987; Mayntz, M. & Laudig, F. 1983).

Any voluntary milking process characterized by a decreased number of clusters and increased number of milkings per day will make this type of teat treatment even worse (Mayntz, M. 1987).

With increased milking intensity, zones of hyperkeratosis arise across the tip of the teat, thereby strongly increasing the risk for infection and mastitis (Rabold, K. 1984).

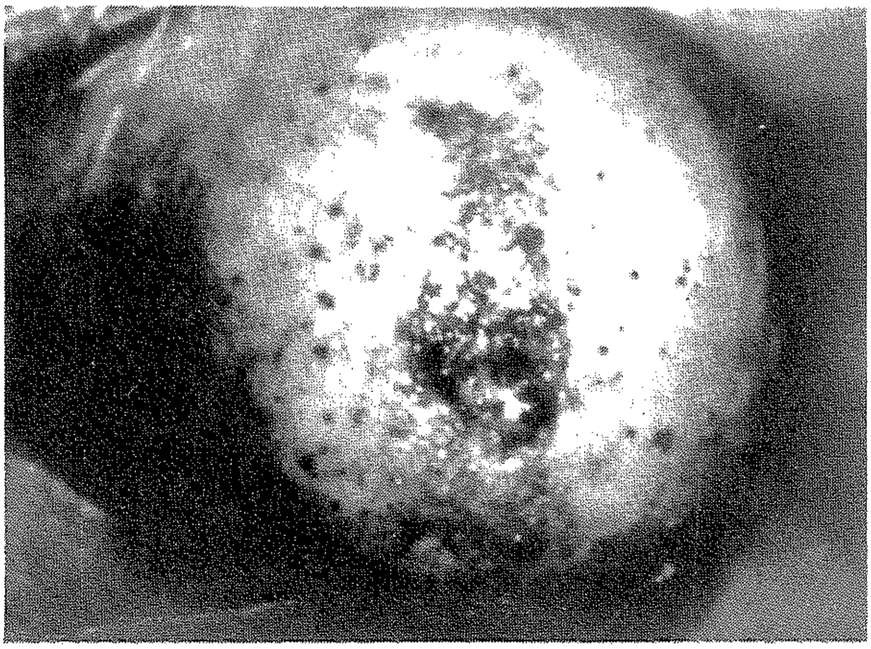


Figure 1. Zones of hyper-keratosis due to increased milking intensity (Rabold, K. 1984).

Experimental teats, milked with linerless equipment, often showed much softer consistency after milking compared with conventional treated teats (Mayntz, M., De Toro, A., Smårs, S., Oostra, H. & Ericson, G. 1989).

The current model of milk flowing through the streak canal is based upon Poiseulle's law (Mayntz, M. & Smårs, S. 1987c):

$$Q = \delta P \cdot \pi \cdot \frac{R^4}{(8 \cdot \mu \cdot L)} \qquad (1)$$

Where

Q = milk flow

δP = pressure difference over the streak canal

R = radius of the streak canal

μ = coefficient of friction

L = length of the streak canal

The milk flow is proportional to a physical factor, i.e. the pressure difference over the streak canal δP and a biological factor, namely the radius of the streak canal R. The friction coefficient μ and the length of the streak canal L are assumed to be constant during one milking period.

3.1 The factors of instantaneous milk flow rate

3.1.1 Biological factors

3.1.1.1 Anatomical limitations of the streak canal

The length of the streak canal varies between 5 and 14 mm (Johnston, T 1938; Venske, C. E. 1940). The canal is slightly cone-shaped with the largest radius at the teat cistern (Johnston, T. 1938; McDonald, J. S. 1968b). The radius of the hind teats is usually larger than the radius of the front side teats (McDonald, J. S. 1968b). The length and the radius of the streak canal increases during each lactation, especially during the second lactation (McDonald, J. S. 1968a).

3.1.1.2 Tonus of the smooth muscles

Most muscles have, even at rest, a ground tension generally called the muscle tonus. This is because some muscle cells are always stimulated by some nerve cells.

In contrast to skeleton muscles, smooth muscles do not react elastically during stretch experiments but as obvious plastic or viscoelastic bodies (Schmidt, R. F. & Thews, G. 1980). This group of muscles cannot be influenced by what is usually described as "the individual's will", unlike the skeleton muscles.

The energy consumption is 100 to 500 times less if one compares the smooth muscles with the skeleton muscles. The contraction speed is, at the same, time 100 to 1 000 times slower for smooth muscles. This makes them particularly suitable for static loads (Schmidt, R. F. & Thews, G. 1980).

3.1.1.3 Variations of the tonus

There is a neurogenic control of the activity of the smooth muscles in the teat, this means that their tonus can be affected both by sensory impressions and the general state of mind.

But there is also a myogenic activity control described as "stretch-reactive contractions" (Mayntz, M. 1984).

Myogenic contractions are spontaneous and cannot be derived from a stimulus originating from outside the body. As also in the heart, the stimulus is generated within the muscle itself. Contractions due to strain are very important for the automatic regulation of blood vessels and whether or not there are disturbances in the central nerve system (Schmidt, R. F. & Thews, G. 1980).

Activity of the smooth teat muscles were often observed. Strong longitudinal contractions of the teat are followed by slow relaxations and prolongations. An increased pressure in the udder cistern provoked by ejection and/or long milking intervals was thought to be the trigger (Sambraus, H. 1971). The longer milking intervals compared with the suckling intervals are pointed out in an ethological paper (Mayntz, M. 1988). Therefore, the occurrence of teat contractions increases suddenly four hours after the last milk withdrawal. Figure 2 gives a survey over current knowledge and hypotheses of smooth muscle activity between milking.

Cause		
Replacement of milk from alveoli and small ducts to large ducts and udder and teat cistern by ejection.	Trickling of milk into the udder and the teat cistern, especially due to long milking intervals combined with high daily yield.	Pressing of milk squirts from the udder into the teat cistern due to the weight of the upper quarters during the resting period of the cow.

↓

Trigger
Stretching of single unit smooth muscle fibres

↓

Result
Myogenic contraction

↑

Function	
Support of the tightening function of the sphincter, which should be hazarded when fibre stretching is continued.	Pumping the milk which continuously stretches the fibres of the teat's wall and of the sphincter back from the teat into the udder cistern.

↑

Physiology				
Single unit smooth muscles, which even without nervous excitement, react with contractions to stretching.	Rapid phasic rhymicity of the sphincter region.	Neurogenic activation of α-receptors by nor-adrenaline	High concentration of nor-adrenaline and a more intimate neuro-effector arrangement in the sphincter region.	Pseudo-peristaltic proximal contractions starting at the sphincter and continuing into the teat's base.

Figure 2. Current knowledge of and hypotheses on the physiology and function of teat smooth muscle activity between milk withdrawals (according to Mayntz, M. 1988).

3.1.2 Physical factors

The pressure difference over the streak canal depends upon two variables:

- the pressure in the udder
- the atmospheric pressure outside the teat

The udder pressure is largest at the start and decreases gradually during milking. The initial pressure increases if a stimulation results in an ejection of milk from the alveoli. A longer interval between milking events also increases udder pressure, as does high milk production (Schmidt, G. H. 1971; Reitsma, S. Y. 1977).

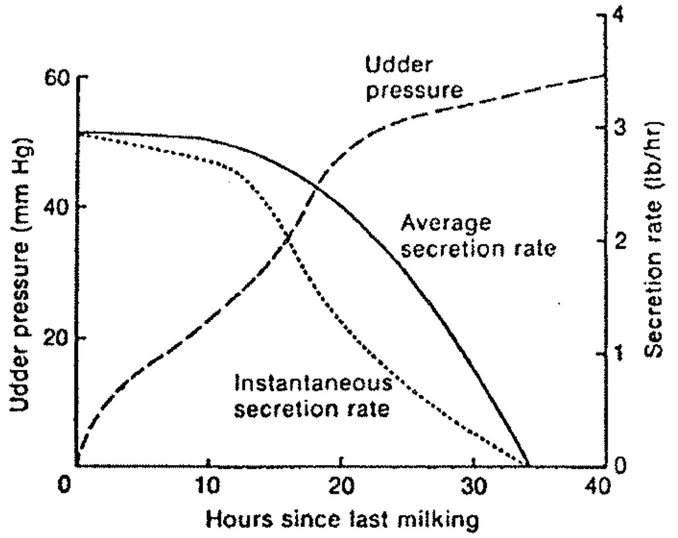


Figure 3. Relationship of udder pressure to secretion rates of dairy cows (Reitsma, S. Y. 1977).

The vacuum applied by conventional technique is usually at 50 kPa. This figure drops to about 35 kPa when milk is transported in the cluster. An increase in milk flow thus results in a decrease of teat tip vacuum (Worstorff, H. 1987).

3.2 Criticism of the conventional model

The milk flow through the streak canal depends only on the pressure difference over the canal provided that the streak canal does not change its radius during the vacuum phase, i.e. neither hormonal or mechanical factors may influence the streak canal.

This assumption seems to be true, at least during that part of the vacuum phase when milk flow is at peak rate. Milk flow should depend only on pressure difference if one accepts the hypothesis that the radius of the streak canal, within certain limitations, only depends on the pressure difference over it.

> "The width of the canal should then be determined, principally and within anatomically set limits by the pressure gradient across the canal." (Isaksson, A. & Sjöstrand, N. 1984).

This statement has, however, poor support from experimental results.

During a study on the influence of stretching or evacuation frequency on flow rate in a linerless system it was shown that the milk flow varies considerably between different evacuation phases although the pressure patterns remained constant, as is depected in Figures 4 and 5 (Delwiche, M., Scott, N. & Drost, C. 1982; Mayntz, M. & Smårs, S. 1987a; Mayntz, M. & Smårs, S. 1987b). Isaksson asserts that these fluctuations in milk flow depend on a restriction of milk flow into the teat cistern (Isaksson, A. & Sjöstrand, N. 1984). However, these fluctuations were observed both during conventional milking and during milking with linerless equipment and disappeared when the myogenic and/or the neurogenic activity control were abolished pharmacologically (Delwiche, M., Scott, N. & Drost, C. 1982; Delwiche, M., Scott, N. & Drost, C. 1984; Mayntz, M. & Smårs, S. 1987a; Mayntz, M. & Smårs. S, 1987b).

The differences in milk flow rate between vacuum phases cannot be explained in terms of pressure differences across the streak canal since these are constant if one assumes that equation 1 is valid, i.e. when the radius of the streak canal is maximal.

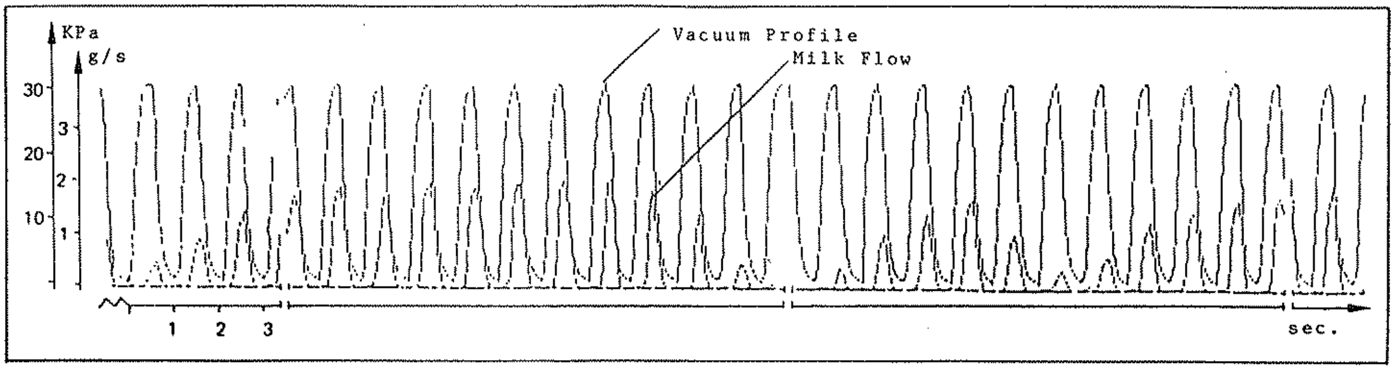


Figure 4. Milk flow oscillations at 0.95 Hz pulse frequency (Mayntz, M. & Smårs, S. 1987b).

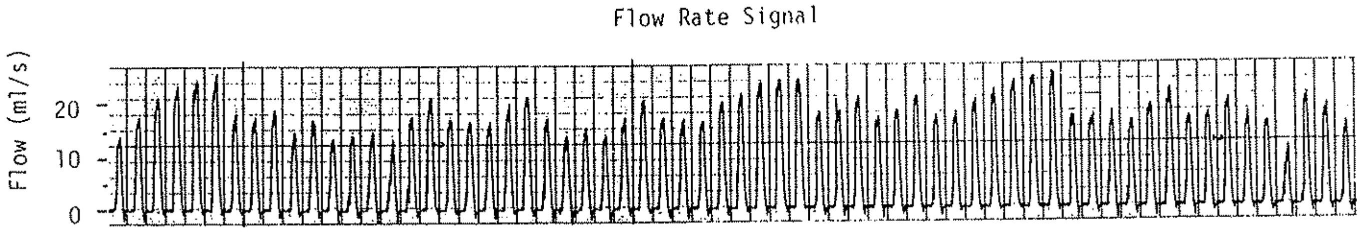


Figure 5. Milk flow oscillations at 1.00 Hz pulse frequency (Delwiche, M. 1981).

Changes in milk flow rate can then only be explained by means of a variation in the streak canal radius during the different vacuum phases.

The conclusion is that the pressure difference has two essentially different functions:

- the opening function of the streak canal by stretching the fibres of the sphincter (Reitsma, S. Y. 1977).
- the transport function of milk through the streak canal in accordance with equation 1 (Bernabé, J. and Peeters, G. 1980).

3.2.1 Opening as a function of pressure difference

Stretching of the muscles results in a widening of the teat canal if one assumes that the teat tip volume is constant. A large pressure difference over the streak canal results in a larger teat stretching, i.e. there is a larger teat canal diameter than would result from a smaller pressure difference.

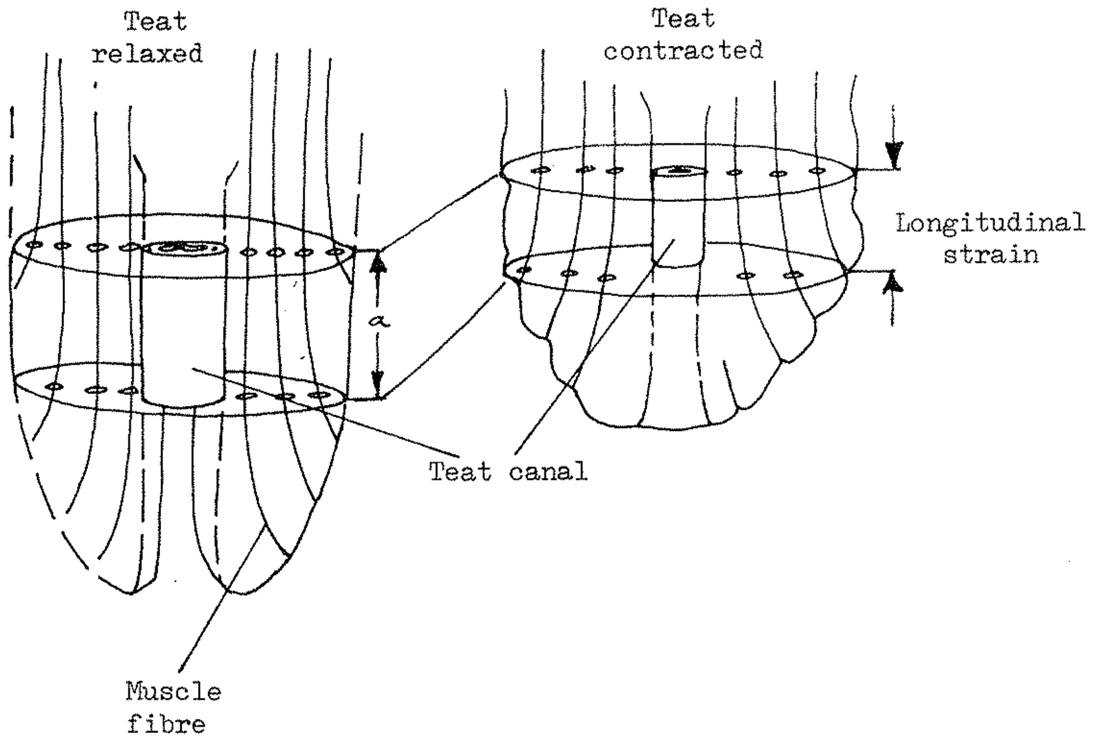


Figure 6. Teat tip volume (according to Williams, D. M. and Mein, G. A. 1980).

<u>3.2.2 Transport as a function of pressure difference</u>

From equation 1 it follows that $Q = K \cdot \delta p$. Further arrangements of this flow model result in Q depending on δP and D, the diameter of the streak canal.

$$Q = 746.24 \cdot (D^{19} \cdot \delta P^{4})^{(1/7)} \tag{2}$$

From equation 2 it may be concluded that the diameter of the streak canal has a major impact on milk flow (Scott, N. R. & Reitsma, S. Y. 1978). See Figure 7.

The reason for the decrease in the equation's derivate may be explained by an increase in milk flow resulting in an increase in dynamic pressure fall over the streak canal. Another explanation might be that there is an active biological system that decreases the teat canal diameter at high milk flow rates.

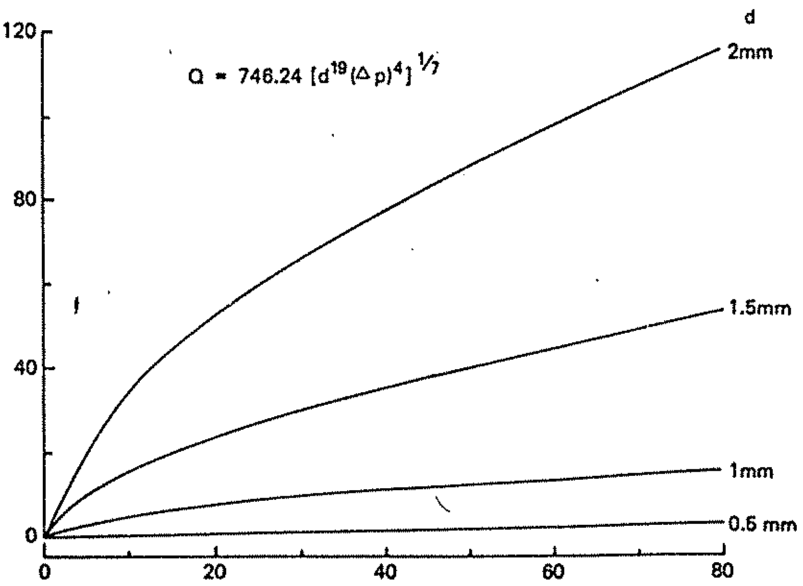


Figure 7. Calculated milk flow rate as a function of δP (Scott, N. R. & Reitsma, S. Y. 1978).

<u>3.2.3 Interaction between pressure difference and muscle activity</u>

Beside the frequency of stretch, the vacuum pattern may also influence the actual streak canal diameter (Mayntz, M., Smårs, S. & Laudig, F. 1989; Mayntz, M., de Toro, A., Smårs, S. Oostra, H. & Ericson, G. 1989). In general, the muscle fibres should only be stretched when relaxed or have not been subjected to on-going contraction (Mayntz, M. & Smårs, S. 1987c).

4 PHYSICAL PRINCIPLES FOR THE MEASUREMENT OF INSTANTANEOUS FLOW RATE

4.1 Principles of measuring flow velocity

The principles discussed in this paper are based on measuring the velocity of milk through a small pipe. If the average velocity through the pipe and its cross flow area are known one can calculate the flow through the pipe with a simple formula.

$$Q = \bar{v} \cdot A \tag{3}$$

Where
Q = fluid flow
$\bar{v}$ = mean velocity of the fluid
A = cross flow area

However, is it not a simple matter to measure flow velocity. Due to frictional forces the velocity profile is parabolic. The formula of this profile changes with the velocity of the fluid. It is almost a straight line for small flows and its form changes gradually towards a more parabolical shape with increasing velocity. In addition to a proper calibration it is of the utmost importance that one measures the flow always at the same place in the tube.

4.2 Measurement based on the Doppler effect

The Doppler effect can be divided up in two different categories:

- stationary transmitter with a movable receiver
- movable transmitter with a stationary receiver

Both categories are utilized simultaneously in the device which we used. The fluid performs as a movable receiver towards a stationary transmitter, a piezoelectric crystal, and as a movable transmitter towards a stationary receiver, also being a piezoelectric crystal.

The Doppler effect consists of the receiver not receiving a wave of similar frequency to that of the transmitted wave if the relative velocity between the transmitter and the receiver differs.

When a transmitter crystal transmits an ultrasound wave with a frequency ω_0 into a tube filled with milk the waves will be reflected in all directions. This is largely done by the gas bubbles in the milk and even to some extent by the fat globules. Usually these gas bubbles are composed of carbon dioxide, nitrogen and oxygen. Some of the reflected energy will be retained by a receiver. The signal received differs from the one that was transmitted due to the Doppler effect of the gas bubbles, i.e. the milk moves in the tube. The equation mentioned below presents the relation between the different parameters connected with this principle.

$$\omega_1 = \omega_0 \cdot \frac{(C_0 + \upsilon \cdot \cos\theta_1)}{(C_o - \upsilon \cdot \cos\theta_2)} \tag{4}$$

Where

ω_1 = the original frequency

ω_2 = the reflected frequency

υ = fluid velocity

C_0 = the speed of sound in milk

θ_1 = the angle between measuring probe and transmitter

θ_2 = the angle between measuring probe and receiver

The measuring probe will only be sensitive to axial reflector movements and insensitive to radial reflector movements if both the transmitter and the receiver are attached to the measuring probe at the same angle. The frequency change $\delta\omega$ will be approximately equal to equation 5 if one assumes that $\upsilon \ll C_0$. The transmitter crystal and receiver crystal are mounted on the measuring probe at the same angle, so that $\cos\theta_1 = \cos\theta_2 = \cos\theta_3$.

$$\delta\omega \approx \frac{(2 \cdot \omega_0 \cdot \upsilon \cdot \cos\theta_3)}{C_0} \tag{5}$$

Where

$\delta\omega = \omega_2 - \omega_1$

This equation shows that $\delta\omega$ is proportional to the axial fluid velocity in the measure probe. If the area of the probe is known, one can easily calculate the flow through it as is shown in the following equation.

$$\delta Q = \frac{(C_0 \cdot \pi \cdot D^2 \cdot \delta\omega)}{(8 \cdot \omega_0 \cdot \cos\theta_3)} \tag{6}$$

A single Doppler frequency is produced if the fluid velocity is constant across the sampling volume. The frequency component due to the Doppler effect is filtered out from the received signal by letting the product of the transmitted and received signals pass through a low pass filter. The part of the product that passes the low pass filter contains the Doppler frequency shift and is converted by a frequency-to-voltage-converter into a analog signal proportional to $\delta\omega$. The average axial fluid velocity can now be calculated if the velocity profile and the position of the sampling volume are known. The sampling volume must be small enough to ensure a uniform fluid velocity within the measuring probe.

However, the milk flow through the streak canal of a cow is turbulent and not laminar. The Reynold's number is 152 000 if one assumes that the streak canal can be seen as a circular cylinder with a diameter of 1 millimetre and that the flow rate of milk through the streak canal is 14 millilitres per second. In this case, the relationship between the flow in any part of the vessel and the average milk flow is unknown. By collecting the Doppler signal from the entire cross section of the flow vessel, the average instantaneous fluid velocity can be determined accurately. The angle between the receiver and the transmitter crystal and the milk vessel are chosen in such a way that their intersection fields create a flat-sided sampling volume the measuring probe. Consequently, the average frequency of the Doppler spectrum corresponds directly to the average axial fluid velocity.

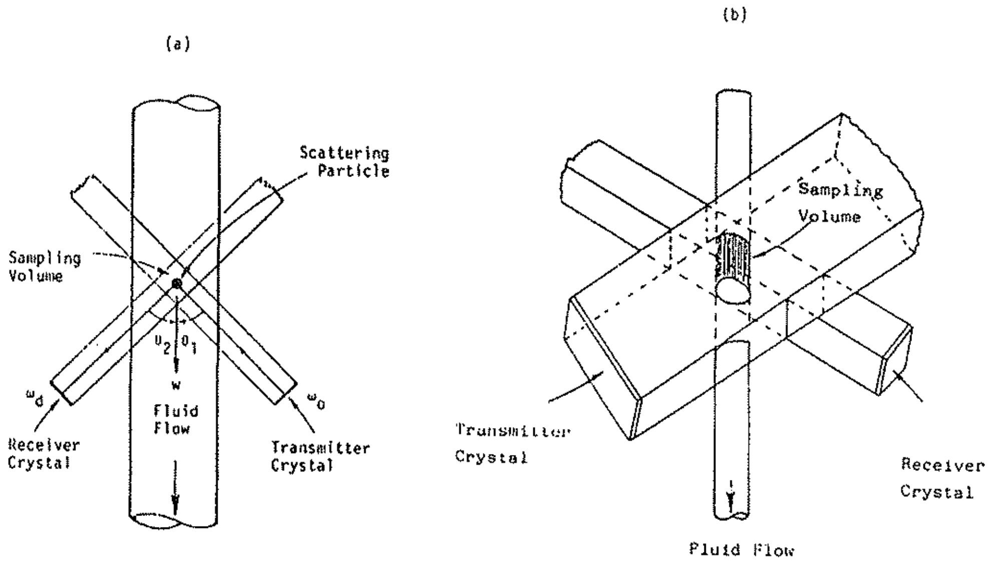


Figure 8. Uniform illumination of the vessel for unknown velocity profiles (a) Crystal, vessel and fluid configuration for flow measurement using back-scattered ultrasound (b) (According to Delwiche, M. 1981).

4.3 Measurement based on variable pressure fall

This flow metering involves placing a constriction in the fluid pipe. This constriction causes a pressure drop which varies with the flow rate. Thus, by measuring the pressure drop, it is possible to measure flow rate.

There are different types of constrictions: The sharp-edged orifice, the Venturi tube, the Dall flow tube, the flow nozzle and the laminar flow element. We chose the sharp-edged orifice because it is simple in construction, low in cost and there is a large volume of research data available. Further, is it especially useful in experiments under difficult conditions.

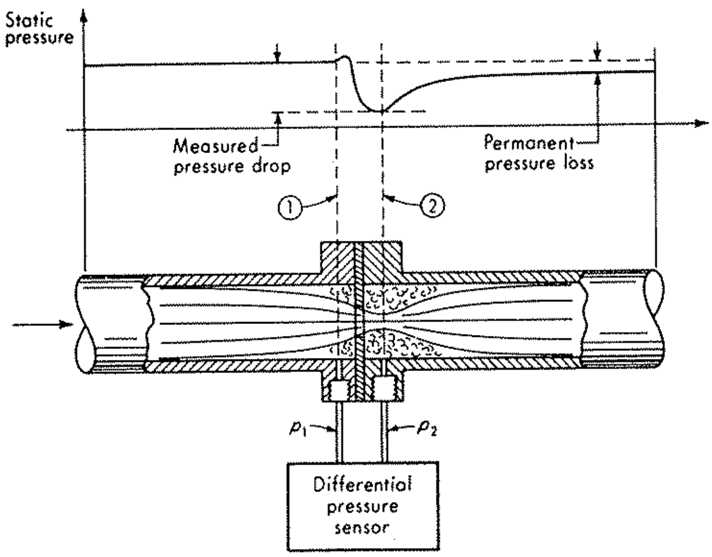


Figure 9. Orifice flow-metering (Doebelin, E. O. 1986).

If one assumes a two dimensional flow of an incompressible fluid with no internal friction and without any energy exchange with the pipe, theory gives the volume flow rate Q_v as

$$Q_v = \frac{A_{2f}}{\sqrt{1-(A_{2f}/A_{1f})^2}} \cdot \sqrt{2 \cdot \frac{(P_1 - P_2)}{\rho}} \qquad (7)$$

Where

A_{1f} = cross section flow area where Q_1 is measured

A_{2f} = cross section flow area where Q_2 is measured

ρ = fluid mass density

P_1 = static pressure at point Q_1

P_2 = static pressure at point Q_2

To obtain Q_v it is necessary to know A_{1f}, A_{2f} and ρ and to measure the pressure difference between P_1 and P_2. However, the experimental situation differs from the assumptions of the theoretical model to such an extent that the establishment of experimental correction factors is necessary for acceptable accuracy. One deviation from the theoretical model is that Q_1 and Q_2 are not obtained from the corresponding pipe and orifice diameter but from the areas of the actual flow cross section. The pipe and orifice diameter are susceptible to practical measurement. Furthermore, A_{1f} and A_{2f} change in dimensions with changing flow rate due to flow geometrical changes. As no fluid exists with no internal friction, the assumption of no energy exchange cannot totally be fulfilled. This affects the measured pressure drop and results in a permanent pressure drop.

To compensate for all these deviations, a calibration is necessary.

A discharge coefficient C_d may defined by:

$$C_D = \frac{Q_A}{Q_C} \tag{8}$$

Where

Q_A = actual milk flow rate

Q_C = measured milk flow rate

and thus

$$Q_A = \frac{C_D \cdot A_2}{\sqrt{1-(A_2/A_1)^2}} \cdot \sqrt{2 \cdot \frac{(P_1 - P_2)}{\rho}} \tag{9}$$

Where

A_1 = pipe cross section area

A_2 = orifice cross section area

The discharge coefficient of a certain measuring probe varies, especially with Reynold's number N_R at the orifice. The calibration is therefore only valid for fluids with the same Reynold's number. Therefore, it was necessary to use milk as the calibration fluid.

C_D values are tabled for certain standard dimensions and measuring points. But these tables include pipe diameters from 50 millimetres onwards and for Reynold's numbers above 10 000. As our first measuring probe was designed to be connected to a milking tube, an appropriate maximum pipe diameter was 14 millimetres.

As was shown in equation 7, flow rate is proportional to $\sqrt{\delta P}$. A change in pressure difference with a factor 10 results in the flow rate changing only with a factor of about 3. Unfortunately, δP measuring equipment becomes inaccurate below circa 10 % of its full-scale measuring range. This is a typical disadvantage of all sorts of obstruction meters, except laminar flow elements. This disadvantage results in that this type of equipment cannot be used below circa 30 % of its maximum flow rate without losing precision.

Another disadvantage with obstruction meters is that they cause difficulties when measuring pulsating flow, where the average flow rate has a fluctuating component superimposed on it, due to the square root non-linearity.

For instance, consider the following example, a flow Q where:

$$Q = Q_{av} + Q_p \cdot \sin \omega t \qquad Q_p < Q_{av} \tag{10}$$

Where

Q_{av} = average flow rate

Q_p = peak flow rate

and a flow meter with the following characteristic

$$\delta P = K \cdot Q^2 \tag{11}$$

Where

K = constant

Combining equation 10 with equation 11 results in a equation that acts as input to the measuring system.

$$\delta P_{av} = K \cdot (Q_{av}^2 + 2Q_{av}Q_p \sin \omega t + Q_p^2 \sin^2 \omega t) \qquad (12)$$

If the pressure measurement probe has a low pass filtering characteristic, it will tend to read the average value of δP according to the following equation

$$\delta P_{av} = K \cdot \left(Q_{av}^2 + \frac{Q_p^2}{2} \right) \qquad (13)$$

As a result, by computing Q_{av} from the measured δP_{av} using $Q_{av} = \sqrt{\frac{\delta P_{av}}{K}}$, we calculate a flow rate higher than actually existed. This means an over-estimation of the real flow rate.

Another disadvantage with this type of measuring device is that when flow rate must be integrated over a longer period, the square root of the pressure signal must be taken before integration or, if this is not the case, a compensation for this must be included in the integrating device.

5 STEPWISE DEVELOPMENT OF MILK FLOW RATE

5.1 Doppler device attached to teat

5.1.1 Description of the experimental teat cup

The experimental teat cup has two specific functions; to apply the planned pressure pattern to the teat and to collect the milk. It consists principally of a straight tube furnished with a specially designed silicon mouthpiece, as depicted in Figures 10 and 11, providing a smooth contact of the cup to the teat base and a seal against atmospheric pressure. Three different sizes were made, so that cows with different teat sizes could be milked. A float valve at the bottom of the teat cup functions to cut off claw vacuum during the atmospheric phase and to allow milk to flow out during the vacuum phase. The lower side of the float was connected to a rubber strip mounted on the bottom of the teat cup in a special way as demonstated in Figure 10. This construction made it possible to maintain a rate of outflow that corresponded reasonably well to the inflow that had to be evacuated during an evacuation phase. In this way the actual pressure pattern could be kept remarkably close to the one intended despite a very simple pressure regulation during the initial experiments. The milking chamber vacuum was monitored with a pressure transducer mounted in the chamber wall 40 millimetres below the upper edge of the teat cup. In addition, an air supply tube is coupled to the teat cup and a third small opening exists for the cables of the Doppler device.

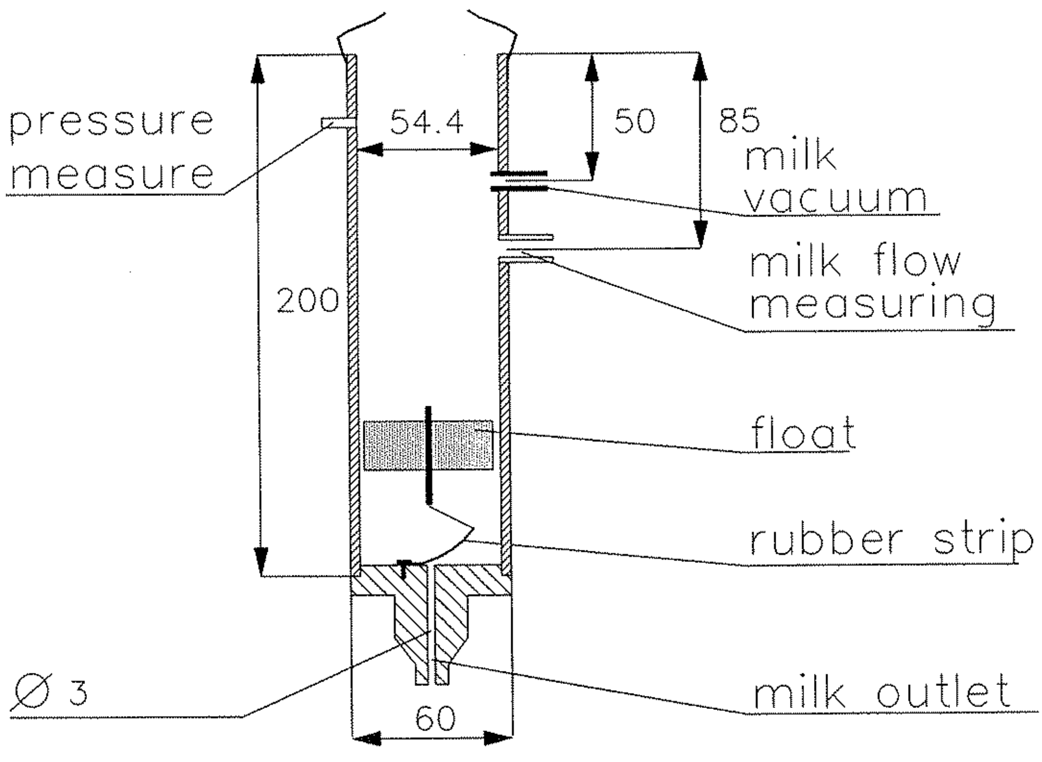


Figure 10. Experimental teat cup.

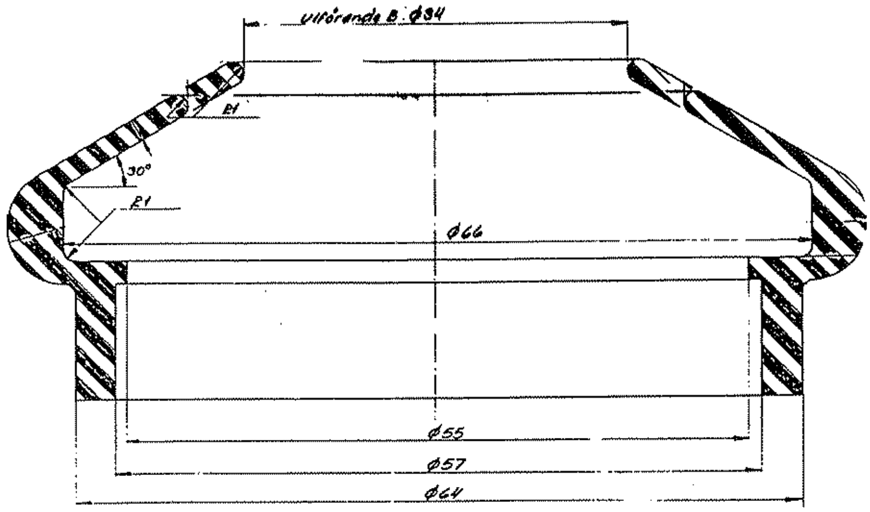


Figure 11. Specially designed silicon mouthpiece.

5.1.2 Description of the measuring probe

A simplified cross section of the flow probe is given in Figure 12. The entire probe was made of plexiglass. The Doppler device used by Delwiche was filled with water between the two crystals and the milk tube in order to provide a good acoustic coupling between the milk and the piezoelectric crystals (Delwiche, M., Scott, N. & Drost, C. 1980). In our case, no such carrying medium was needed other than the plexiglass itself. Further, gDelwiche used a Doppler device with a frequency of 2.1 MHz. We used a Doppler device with a frequency of 10 MHz. In this way, the spread of the ultra sound wave was much less and this shielding-off the ultra wave was no longer necessary.

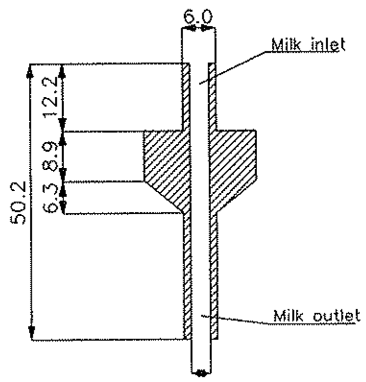


Figure 12. Doppler measuring device.

The measuring probe was made at the Department of Medical Technique at the Malmö General Hospital. The original measuring range of the probe, however, was only between zero and four millilitres per second. Originally it was designed for measuring the blood flow in human blood vessels. This was far below our demands, since the maximum milk flow registered by Delwiche was about forty millilitres per second. This means that the flow range of the probe had to be extended.

The theory explained in section 4.2 cannot be used without a proper calibration of the milk flow probe. The ultra wave received by the receiving crystal was made up of different frequencies with different amplitudes. This was not only caused by the different sizes and location of the gas bubbles in the milk but also by the changing flow profile across the measuring vessel. The equipment we used calculated the milk flow by measuring the number of times the Doppler signal increased to zero. This worked fairly well during low milk flow but poorer during higher milk flow. During high milk flow rate the high frequency waves were superimposed on waves with a lower frequency, see Figure 13. Consequently, the meter calculated the number of times when the amplitude of the waves of the low frequency part of the signal were zero and not the times when the high frequency waves were zero. Therefore, the measuring method was changed from measuring zero amplitude to measuring the number of changes made in the signal's time derivate, see Figure 14.

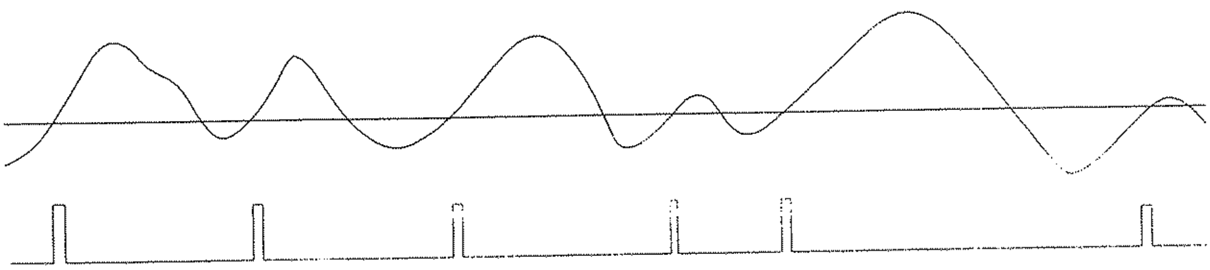


Figure 13. Oscilloscope image showing electronic signal received from the Doppler device. Milk flow is calculated from the number of times when the signal is zero (Smårs, S. 1990).

Unfortunately the measuring instrument became more sensitive to electronical disturbances and random noise, resulting in an upper limit beyond which the measuring range could not be extended. Nevertheless, the measuring range was extended from 4 to 20 millilitres per second.

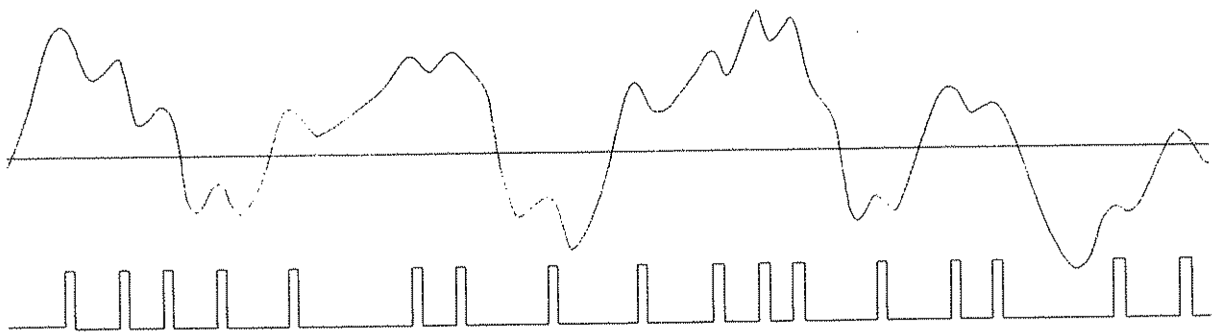


Figure 14. Oscilloscope image showing electronic signal received from the Doppler device. Milk flow is calculated from changes in the signal's time derivate (Smårs, S. 1990).

5.1.3 Additional equipment

A milk container was used in which the total milk yield was collected, as is depicted in Figure 15. In this way could we compare the total measured milk yield with the "true" milk yield. The container was furnished with a centimeter scale so that the milk level in the container could easily be read.

A latex finger cot or sheath was used to connect the teat to the measuring probe, a surgical glove provided the necessary cots. A small opening was made at the end of the finger and a small plastic tube was glued into this opening. The plastic tube had a length of about 5 mm and the same inner diameter as the outer diameter of the Doppler device.

Before an experiment began a large number of cots were produced. Two categories of cots were made, one type for short teats and one for long teats. In previous experiments, three different sizes had been used, small, medium and large. This differentiation was replaced in our case by selecting experimental cows for equalness of teat shape.

At the onset of a measuring period a cassette recorder and a stop watch were started from zero. The milker reported observations or events together with the actual time. This was of great help in the evaluation of the data, which was often done several days later and carried out by people who had not been present during the milking.

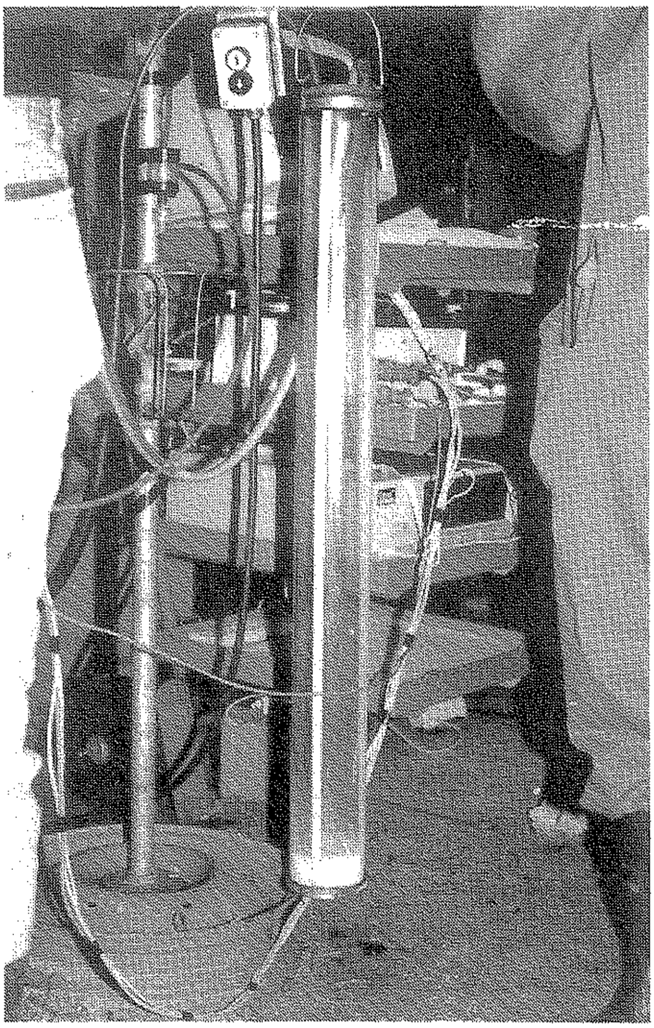


Figure 15. Milk Container.

5.1.4 Calibration

5.1.4.1 Procedures for calibration

Figure 16 explains the basic arrangements for the calibration of the Doppler measuring probe. By placing a milk tank about 3 meters above the probe, the milk flowed through the Doppler device into the beaker that was placed on a scale. It was possible to control the milk flow by means of a restriction in order to imitate different flow rates. The time taken to fill the beaker was simultaneously registered so that the real flow rate during filling could be calculated.

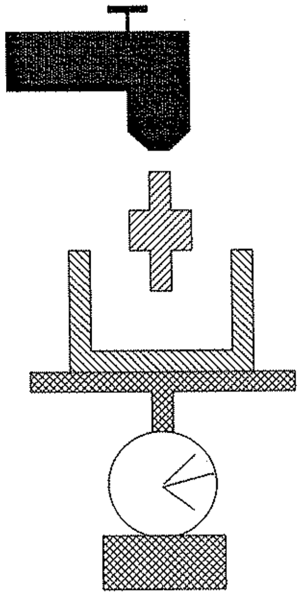
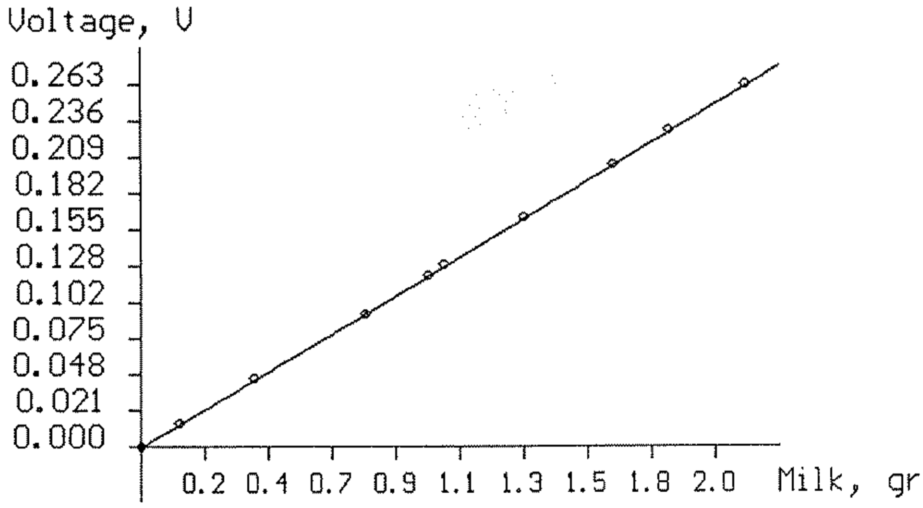


Figure 16. Schematic arrangement of calibration procedure.

The ultra waves are reflected by gas bubbles, as mentioned above (section 3.1.1). The milk used for calibration was at least 12 hours old. This meant that most gasses had dissolved, resulting in a poor reflection of the ultra waves. Blowing compressed air into the milk solved that problem.

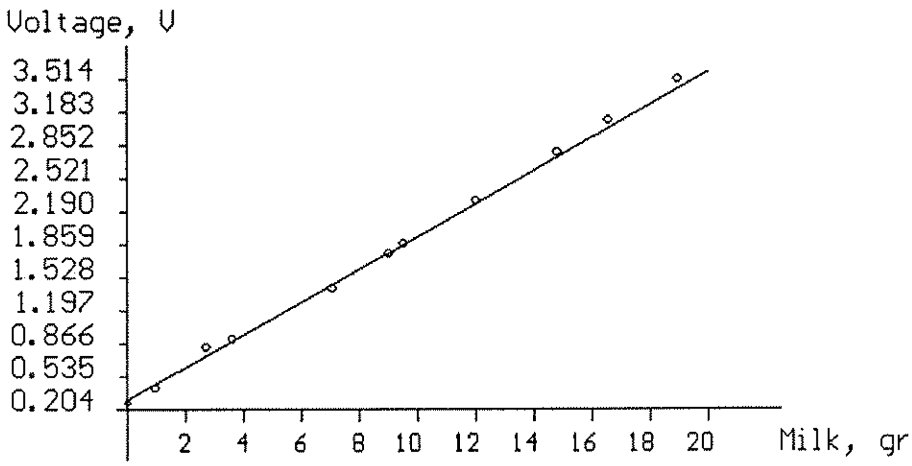
5.1.4.2 Calibration curve

The signal from the Doppler was not a linear function of the instantaneous milk flow as it should be. Therefore, two different regression lines were developed, one for low and the other for high flow situations. It had to be decided whether the registered signal exceeded the point of intersection of the regression lines before evaluating the data



$$Y = -0.006 + 0.0263 \cdot X$$

Figure 17. Calibration curve and equation, low flow rates.



$$Y = 0.204 + 0.1655 \cdot X$$

Figure 18. Calibration curve and equation, high flow rates.

These Figures and equations are only illustrations and not valid for all experiments. These specific equations were used during the experiments in June 1986. In other experiments, we calculated other regression lines.

5.1.5 Practical procedures

A lift, as depicted in Figure 19, was used for every experiment. It has two distinct functions. Firstly, it fixes the cow firmly, and secondly, the height of the cow above the ground can be adjusted to a comfortable height for the milker. As a curiosity it may be noted that some cows appear to suffer from "acrophobia". The lift was fastened firmly, with four bolts, to the ground. Nevertheless was it possible to move the lift to another place, if required, by means of four small wheels that could be mounted the each corner of the lift.

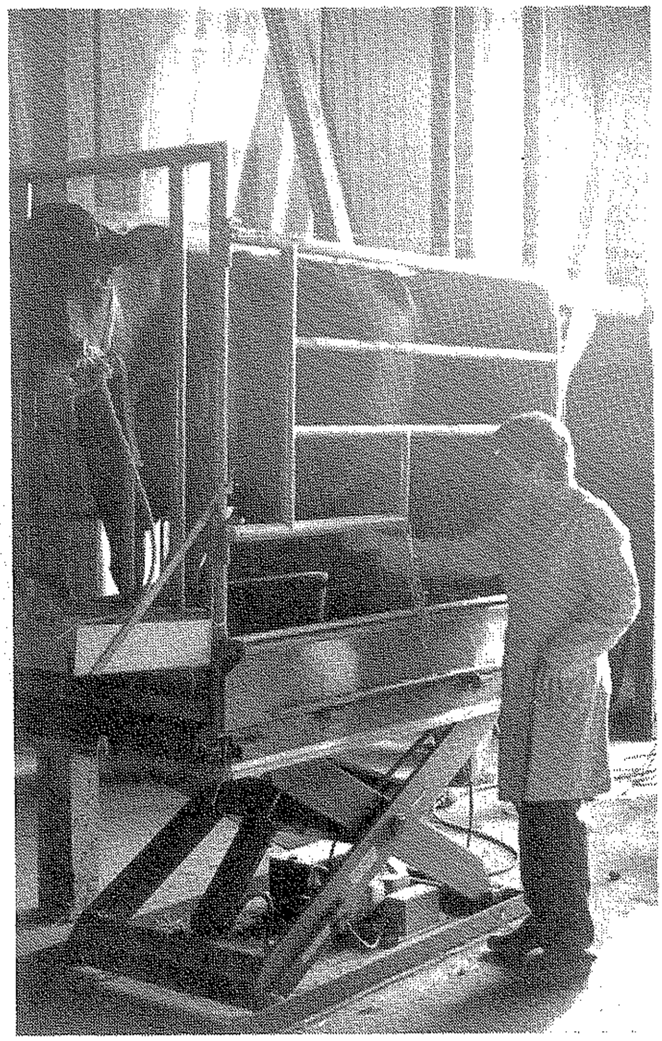


Figure 19. Lift used for milk-experiments.

A cow was milked with the experimental teat cup only on the left rear teat, the other teats were milked with conventional technique. All teats were cleaned carefully with warm water. The left rear teat was shaved before an experiment started if necessary. This made it easier to attach and remove sticking-plaster and it improved contact between the teatbase and the mouthpiece of the experimental teatcup considerably.

Before the latex cot was rolled onto the experimental teat, molten beeswax was spread on the surface of the teat. This was done to increase the friction between the teat and the latex cot in order to minimize cot-slippage during milking. But this was not sufficient. To prevent the removal of the cot during milking under all conditions the latex cot was fixed to the teat with help of some pieces of sticking-plaster. It was necessary to shave the teats and some part of the udder before a experiment began so that the sticking-plaster would stick adequately. For the same reason the teat and teat base were cleaned carefully.

One had to ensure that the latex cot was fitted snugly against the teat end, otherwise the teat canal and the opening of the measuring probe would not be in line, thereby giving rise to an increased flow resistance. Sometimes the cot had to be fixed with sticking-plaster at the teat's base

When the latex cot was in place, the Doppler device could be attached. Previously the Doppler had been connected to the teat cup so that after the attachment of the Doppler the measuring could begin.

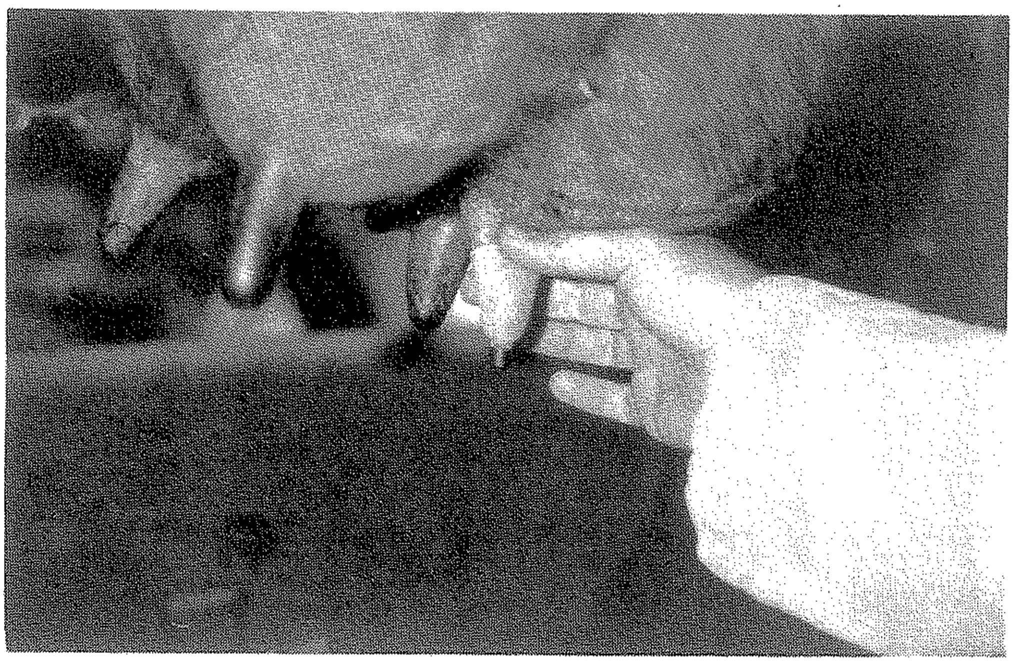


Figure 20. Latex cot rolled on to experimental teat.

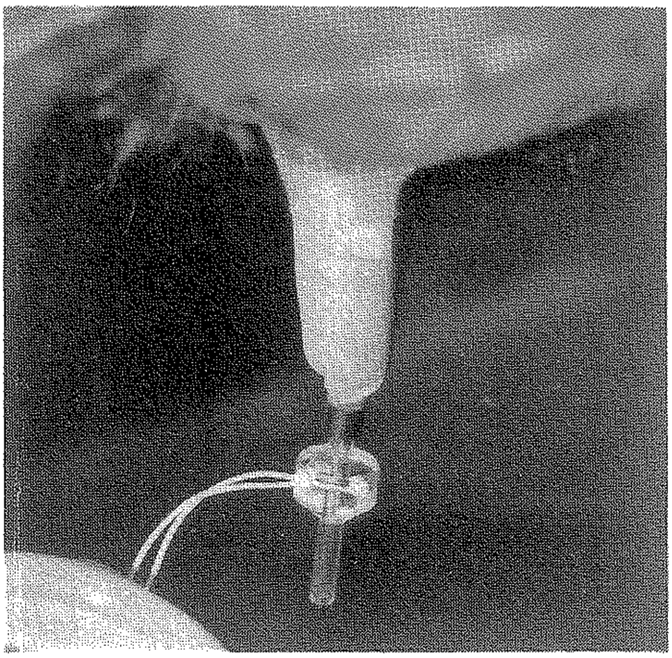


Figure 21. Doppler device attached to latex cot.

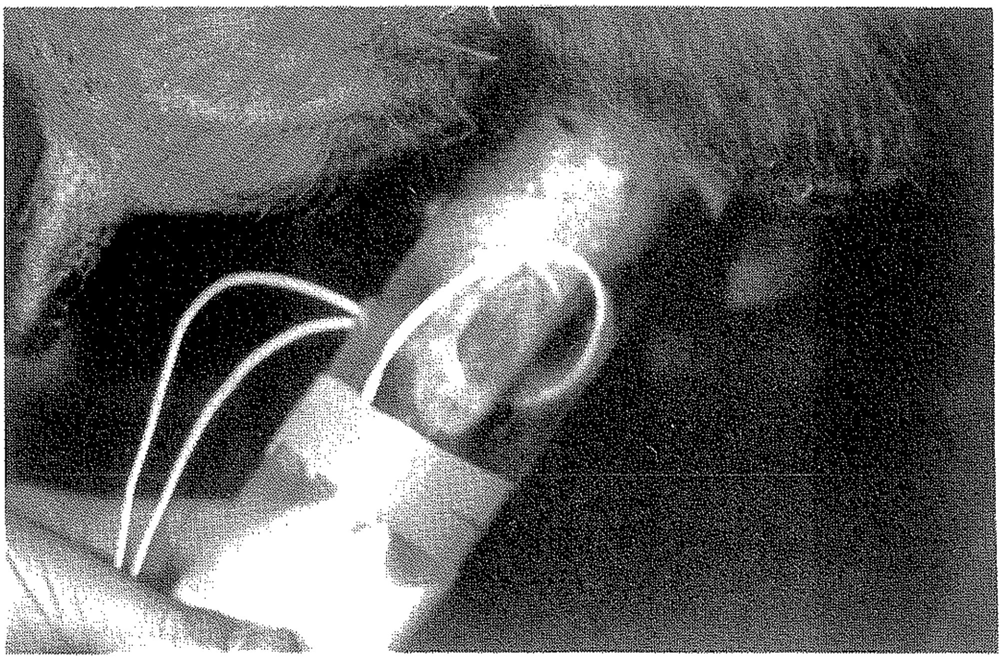


Figure 22. Experimental teat cup in action.

Close observations of the cot's behaviour during milking were necessary.

5.1.6 Expectations

As mentioned above, the registered changes of instantaneous flow rate were intended to be interpreted as muscle activity. Therefore it was fully understood from the beginning that this method would lead to a serious error as the latex cot would interfere to an unknown extent with this muscle activity. However, this method was described in the literature and it therefore seemed appropriate to start with an already developed method. It must also be underlined that this equipment was used only during the initial experiments.

5.1.7 Experiences

5.1.7.1 Characteristics of measuring probe

Figures 23 and 24 show two different types of vacuum profiles; triangular and square-shaped. The top curves illustrate the vacuum profiles and the bottom profiles the milk flow.

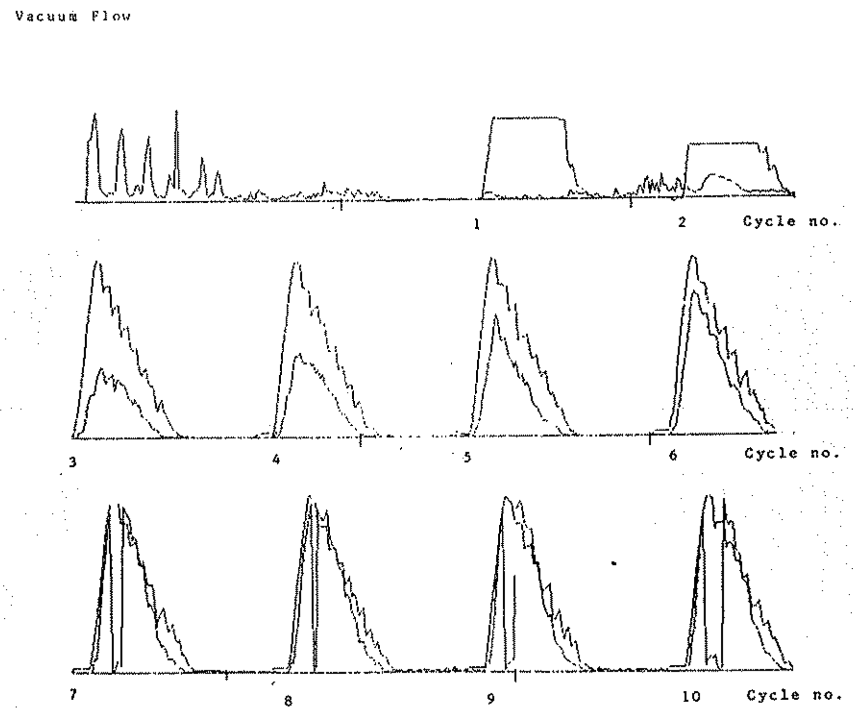


Figure 23. Milk flow profile in combination with triangular-shaped vacuum profile.

Figure 23, depicting a number of triangular-shaped profiles, show two interesting features. Firstly, the small peaks illustrate squirts of milk being forced through the measuring device by hand, secondly, cycle numbers 7, 8, 9 and 10 show that the Doppler repeatedly bottomed as the milk flow rate exceeded 12 millilitres per second.

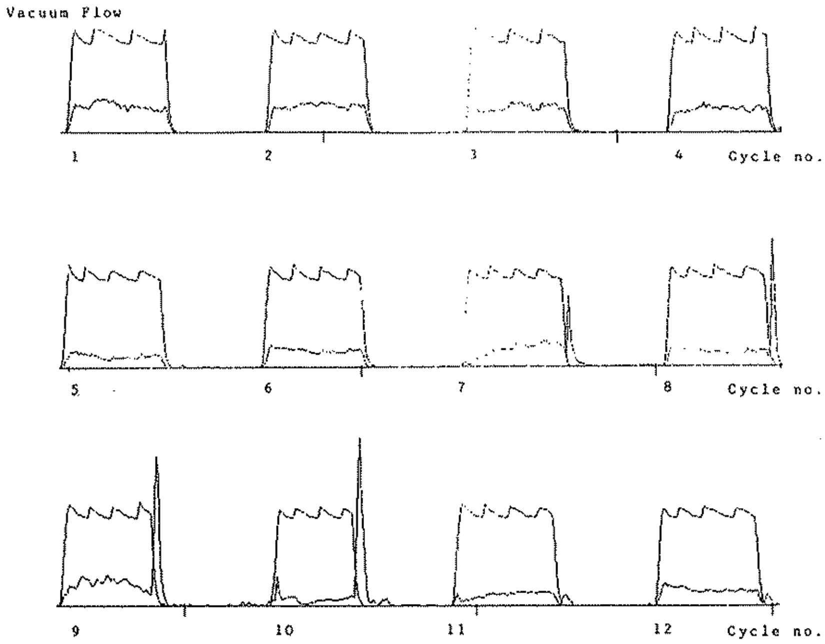


Figure 24. Milk flow profile in combination with square-shaped vacuum profile.

Cycle numbers 7, 8, 9 ,10 and to a lesser extent cycle numbers 11 and 12 in Figure 24, show that a varying balloon-like space developed beneath the teat tip during milking. This is clearly expressed in the high milk flow rate peaks at the end of the vacuum cycles.

5.1.7.2 Further experiences

Some of the major negative sides of this method are:

- The cot and especially the sticking-plaster restricts the teat in its natural movements and thus probably affects the muscle activity and the opening of the streak canal.
- The measuring tube has an internal flow resistance due to its length, diameter and material. It may be regarded as an artificial elongation of the streak canal.
- The beeswax must be of the right temperature: if too hot the cow will object and if too cold it will be lumpy.
- It is difficult to attach the latex cot to the teat in the correct manner. The opening must be in line with the streak canal in order to reduce the flow friction. If this could not be achieved a milk bell would arise resulting in a phase displacement.
- The tip of the cot cannot be tightly fixed to the teat, thus resulting in a balloon-like space of different size developing beneath the teat tip during milking.
- At higher flow rates the additional flow resistance mentioned above resulted in squirts of milk not passing the measuring tube but finding their way between the teat and the cot (Mayntz, M., Smårs, S. & Laudig, F. 1989).
- At flow rates exceeding 12 millilitres per second, the signal from the Doppler repeatedly bottomed and went down to zero (Mayntz, M., Smårs, S. & Laudig, F. 1989).
- When comparing the integrated Doppler signal from a complete milking with the collected amount of milk, an underestimation of about 20 % by the Doppler had to be considered. However, when the flow rate was below 12 millilitres per second, the precision was within ± 5 %.

Due to these problems it was decided that the measuring technique should be reconstructed on the basis of a completely uninfluenced teat.

The milk float was made of foamed plastic, which had to be changed after two to three experiments. A float made of this material is difficult to clean, milk tends to saturate the float after some time, giving rise to a bad smell.

5.2 Contact-free cup combined with a Doppler device

5.2.1 Description of the experimental teat cup

The basic principle of this cup differs entirely from the cup described above (section 5.1.1). The teat cup is divided in two different parts, see Figure 25. The upper part applies the vacuum to the teat and collects the milk. The lower part functions as a pressure equalising chamber in order to establish equal pressure on both sides of the measuring probe. This was necessary because the pump which transported the milk from the upper chamber through the measuring probe had an internal friction that was too low to withstand a pressure difference.

A ping-pong ball placed in the bottom of the lower chamber functioned as a float valve cutting off the claw vacuum during the atmospheric phase and allowing the milk to flow into the milk container during the vacuum phase.

The milk, collected in the upper chamber, flows into the measuring cell, placed directly under the upper chamber. Two electrodes, placed in the measuring cell, provided the information needed in order to regulate the milk level in the regulation cell. In the literature, electrodes were used for similar purposes, i.e. measurement of milk resistance (Schmidt, W. L. 1986). For instance, a galvanic gold-plated copper-coated lead electrode was used. In this case the milk resistance was directly used as a parameter proportional to the milk flow rate and it was of great importance that any change in resistance, due to changes in electrode characteristics, was avoided (Schmidt, W. L. 1986). Since we did not use the same sort of measuring principle, a less complicated electrode could used.

The electrodes used were made of stainless steel with a thickness of 2 millimetres. Each electrode was mounted with a cable clip, so that connection and disconnection could easily be performed.

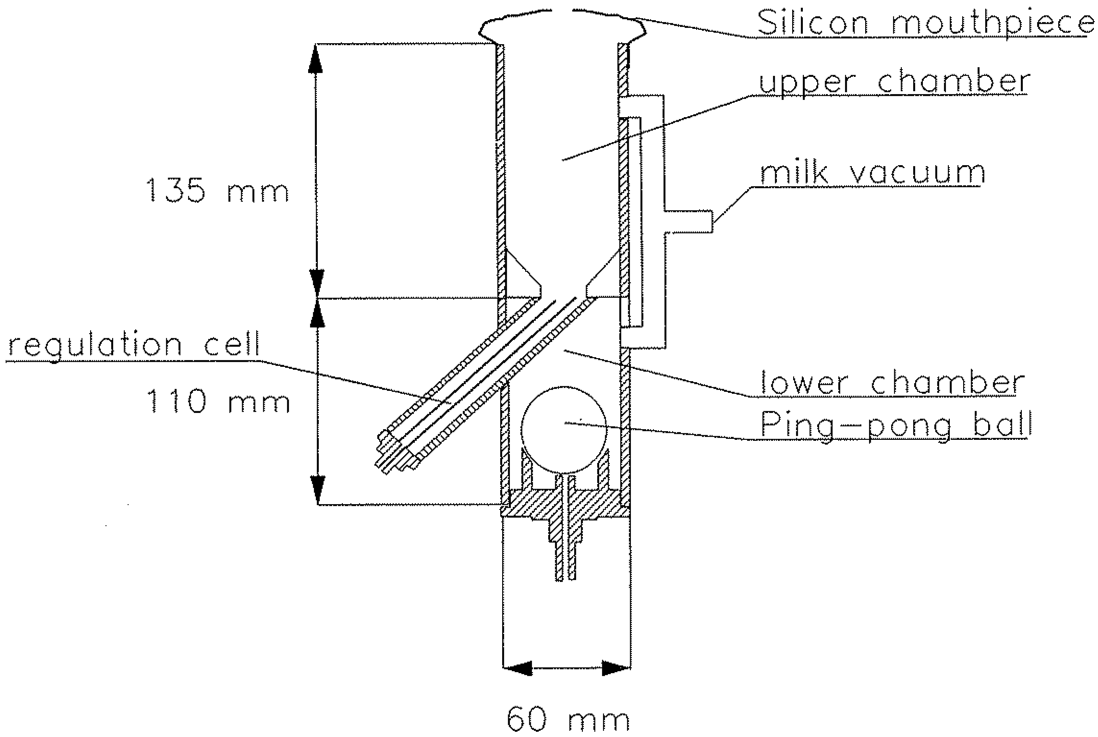


Figure 25. Contact-free experimental teat cup.

5.2.2 Description of the measuring probe

As described in Section 5.1.2

5.2.3 Additional equipment

A small pump, from a car's windshield cleaner was used to transport the milk from the upper chamber into the lower chamber. The main reason for this choice was that the regulation system for this pump was already fully developed by another team at the Department (Brandt, J., Klensmeden, S. & Alness, K). Another reason for selecting this pump type was that it could be operated by a commercial car battery. Although the pump used only 1 ampere, the battery had to be charged every fortnight, because it also powered other peripheral equipment.

The primary reason for process control is to keep a dynamic variable on a fixed level at or near a desired specific value. It is necessary to provide constantly corrective actions to keep the variable constant since the variable itself is dynamic. In our case, the ensemble of milk, regulation cell, milk inlet and outlet form the process. The milk level in the regulation cell is the parameter that should be kept at a constant level, i.e. the dynamic variable. To provide a regulation, the information on the milk level must be fed back to a controlling element, the pump. This is done by means of a electronic circuit. With this feedback it is possible to obtain a closed loop or regulating process. The basic constituents of a regulation system are process, measurement, evaluation and control.

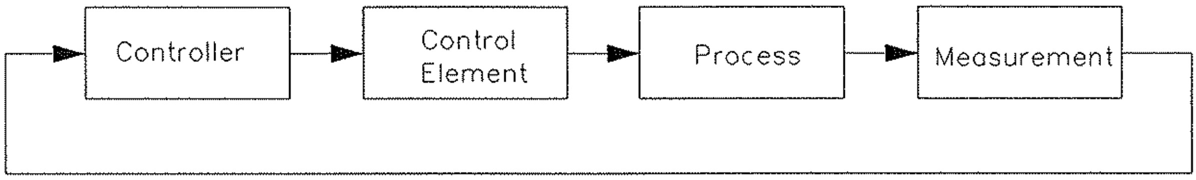


Figure 26. Schematic drawing of the process control system.

The different elements in a process control loop are shown in Figure 26.

Process

As mentioned above, the milk flow into and out of the regulation cell and this, as well as the regulation cell itself, together form the process that should be controlled.

Measurement

To control the dynamic variable in a process it is necessary to have reliable information on the variable itself. Thus it is necessary to measure the variable in one way or another. Generally a device is used that converts the initial measurement and energy of the dynamic variable into a analogous electrical or pneumatic signal. In our case, the resistance between the two electrodes is the variable that varies with a varying milk level in the regulation cell.

Evaluation

In this step a decision is made concerning the way in which the system should be controlled in order to maintain the desired value of the dynamic variable. Usually some sort of controller is used. Nowadays, a controller of this kind is operated generally by means of a computer but this approach was not used in our equipment. The controller is needed for fast decisions and requires an input of both a measured representation of the dynamic variable and a representation of the desired value of the variable, expressed in the same terms as the measured value. The desired value is referred to as the setpoint and the measured value of the variable as the measurement. The evaluation consists of a comparison between the value of the controlled variable and the setpoint and a determination of action required to equal the controlled variable and the setpoint. We used a electronic circuit as a controller which is shown in Appendix 1.

Control element

The control element is the device that provides the required changes in the dynamic variable so that it is brought to the setpoint. This element requires a input signal from the controller, which is then converted into a proportional operation performed by the process. Our control element was a very inexpensive gear-driven pump, which was both relatively small and light.

The resistance between the two electrodes mounted in the regulation cell is reciprocally proportional to the height of the milk level in the regulation cell. Non-linearity can be neglected if only small changes in milk level are allowed in the regulation cell. A small part of the hyperbola may be considered to be a straight line. This means that the changes in resistance between the two electrodes can be used to maintain a constant milk level in the regulation cell. Any change in resistance is converted in proportion to a regulatory system into a voltage that can power a small pump. The pump is used to remove the milk exceeding the desired milk level in the regulation cell. Thus, milk flows into the regulation cell, milk level rises slightly, electrodes detect a small decrease in resistance, resistance is converted into a voltage by the regulatory system which then powers a small pump that removes the amount of milk exceeding the desired value in the regulation cell.

The use of a regulatory system enables a choice to be made among a large variety of different measuring probes. The external flow resistance always found in connection with a measuring probe is easily overcome by using a pump equipped with a strong motor. Moreover, in the present context, when a variable pressure drop meter was used, the artificial resistance was of no concern.

It was important that the regulation system was adjusted in a optimum way. Figures 27 and 28 show the difference in measuring quality between poorly-adjusted and well-adjusted regulation system.

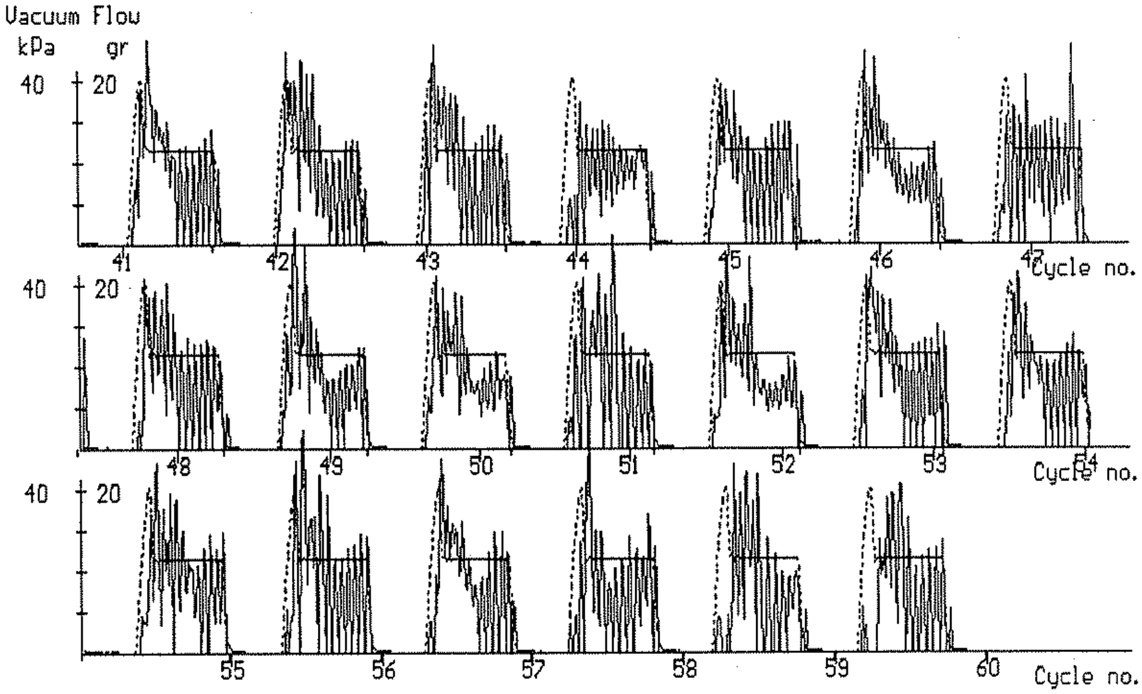


Figure 27. Poorly-adjusted regulation system.

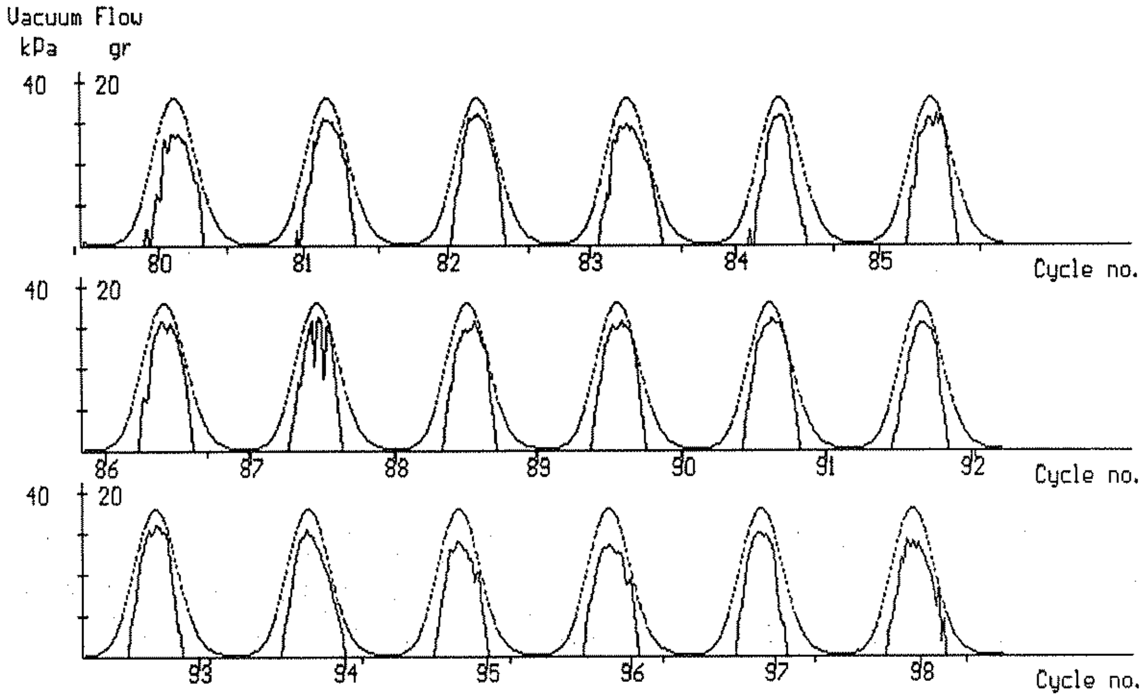


Figure 28. Well-adjusted regulation system.

A flow diagram, such as shown by Figure 27, is due to excessive amplification. The system reacts too fast to any disturbance and over corrects, resulting in a jerky regulation. Such a flow diagram can hardly be used for instantaneous milk flow rate measurement. However, it can provide some information about the mean milk flow rate. The flow diagram in Figure 28 shows a smooth milk flow rate curve. Such curves are first rate. The flow diagrams shown are not made by means of a Doppler measuring device but are actually made with the measuring probe described in Section 5.4.2. Here they serve only as a demonstration of different regulation adjustments.

5.2.4 Calibration

5.2.4.1 Procedures for calibration

A similar arrangement to the one described in Section 5.1.4.1 was used for calibration. However, the pump that evacuates the milk of the upper chamber from the teat cup was used to pump milk through the measuring device during calibration. Different milk flow rates could now be controlled and simulated by means of changing the voltage to the pump instead of using a valve. This arrangement has several advantages compared with the disposition mentioned in Section 5.1.4.1. It was no longer necessary to lift a tank several meters above ground level in order to create a sufficient water column. Only a small amount of milk was needed.

5.2.4.2 Calibration curve

A simple computer program calculated a regression line. Different equations were calculated for different flow ranges. The output signal of the Doppler device is, unfortunately, not linear over a large flow range. During the evaluation of our raw material the computer "decided" which equation should be used. An example of such an equation is shown below.

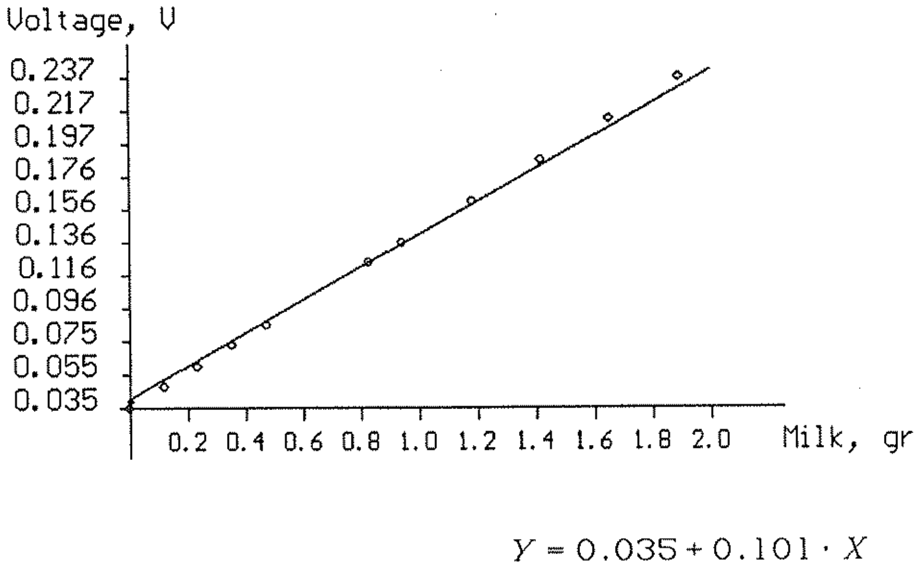


Figure 29. Calibration curve and equation, low flow rates.

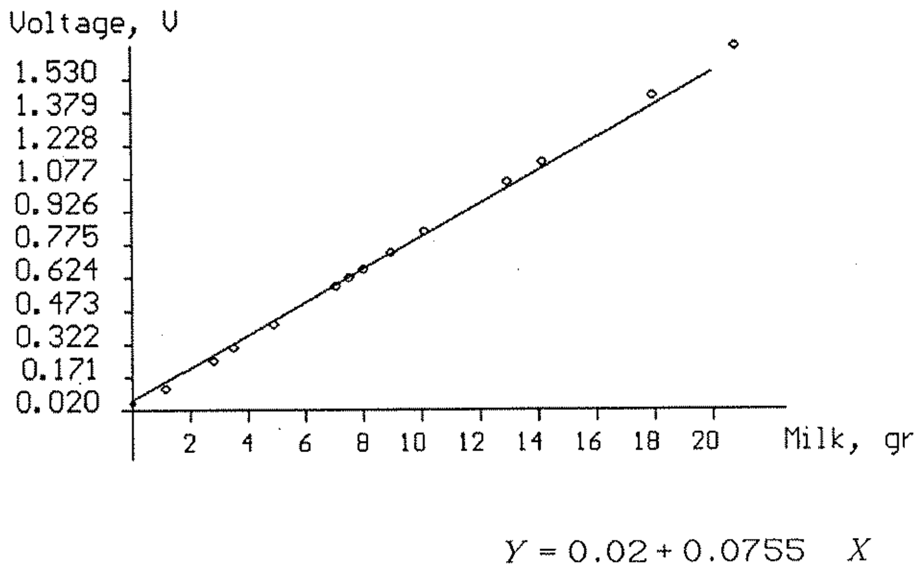


Figure 30. Calibration curve and equation, high flow rates.

5.2.5 Practical procedures

It was necessary to test the Doppler device before milking started in order to check its function. This was done by checking whether the output signal from the Doppler device changed if water was poured through it. The signal could be read on a voltage meter. The most frequent disturbance was caused by poor cable connection.

The teat and udder were cleaned in the same way as described in Section 5.1.5, but the teats were no longer shaved at the start of a milk experiment.

A cassette recorder was used during a milking as described above (Section 5.1.3).

5.2.6 Expectations

A major improvement over the experimental teat cup described in Section 5.1.1 was that the activity of the teat muscles was no longer disturbed. This cup is really capable of allowing the natural activities of teat to proceed undisturbed. In addition no fixation of the teat was used except for the mouth piece, which should result in more uninfluenced contractions and relaxations of the teat muscle fibres.

5.2.7 Experiences

5.2.7.1 Characteristics of measuring probe

When comparing the integrated Doppler signal from a complete milking with the collected amount of milk, an underestimation of about 20 % by the Doppler measuring device had to be considered. However, when the flow rate was below 12 millilitres per second, the precision was within ± 5% (Mayntz, M., de Toro, A., Smårs, S., Oostra, H. & Ericson, G. 1989).

5.2.7.2 Further experiences

In the former construction a small space beneath the teat developed more or less regularly resulting in an uncontrolable artefact. By omitting the latex cot this influence from the measurement technique on registered instantaneous milk flow rate disappeared. The new construction, however, resulted in a constant phase displacement. To a minor extent it consisted of the time needed by the milk to run into the regulation cell, but a more important aspect is that the regulation system itself also has a positioned phase displacement of about 0.2 seconds, which is necessary to avoid the system becoming to jerky. The total phase displacement is constant during an entire experiment provided the adjustments controlling the amplification and the level in the regulation cell are not altered.

The new teat cup functioned very well during the initial experiments. The overall procedures were simplified to such an extent that no measurements had to be repeated on account of, for example, replacement of the measuring probe.

Although the system worked as expected, the measuring probe caused some trouble. During the experiments the signal fell to zero as the milk flow exceeded 12 millilitres per second. The measuring probe clearly had to be redesigned to enable it to measure flows exceeding 40 millilitres per second.

The choice of stainless steel electrodes proved to be very successful. No coating on the electrodes due to precipitation of milk or washing-up detergent was noticed during the experiments.

Initially the cup was designed in such a way that the upper part could be detached from the lower part to make it easier to clean. However, it was found very difficult to seal as air always entered the teat cup between the upper half and the lower half. Therefore the two pieces were glued together, even though the cleaning became more difficult.

The pressure difference over the milk outlet could not exceed 20 kPa. The lifting capacity of the float is not more than 0.28 Newton. Consequently the vacuum level in the milk container had to be changed when vacuum profiles are used with different peak values. This was done very easily between two milkings by turning a screw that controlled the vacuum level in the milk container.

The ping-pong ball did not regulate the milk level as well as the foamed float. Every now and then the ball did not lift after every vacuum phase, but after every second phase. Consequently the milk level in the lower part of the milk cup varied considerably. However, this was no longer a problem since the vacuum regulation system had been improved. The new system not only meant an improved regulation, so that disturbances like the ping-pong ball problem were no longer of importance, but it was now also possible to generate a more complex vacuum profile than previously.

The vacuum profiles depicted in Figures 23 and 28 may be compared. Figure 23 shows a vacuum profile with a great number of disturbances that are generated by the regulation system itself. It was designed to operate in this way and is partly due to the large valves that were used.

The improved vacuum regulation system was able to generate more complex vacuum profiles with a very high level of regulation quality as depicted in Figure 28.

5.3 Contact-free cup combined with the Doppler device after a shunt

5.3.1 Description of the experimental teat cup

As described in Section 5.2.1.

5.3.2 Description of the measuring probe

In order to improve the measuring range of the Doppler device a very simple solution was applied. The general idea was to measure only a fixed part of the milk flow through a tube by means of an initial shunt. The flow resistance of the shunt tube had to be of the same magnitude as the flow resistance through the Doppler device. In this way the measuring range of the Doppler device was approximately increased to twice that of the original. Both the Doppler device and the shunt tube were "melted" in a block of silicon plastic in order to prevent any change in position between them. A change in position would result in a change in flow resistance and the calibration curve for the milk flow would no longer be valid.

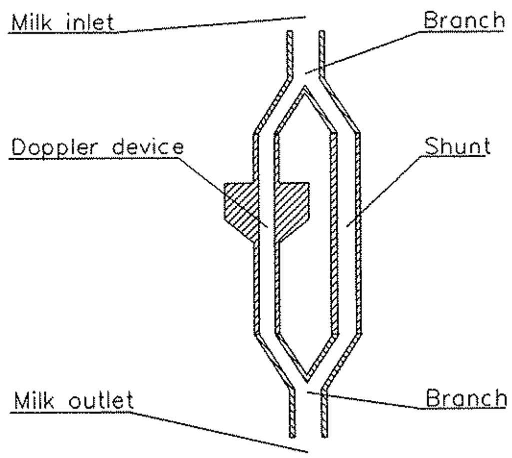


Figure 31. Schematic drawing of the shunted measuring probe.

5.3.3 Additional equipment

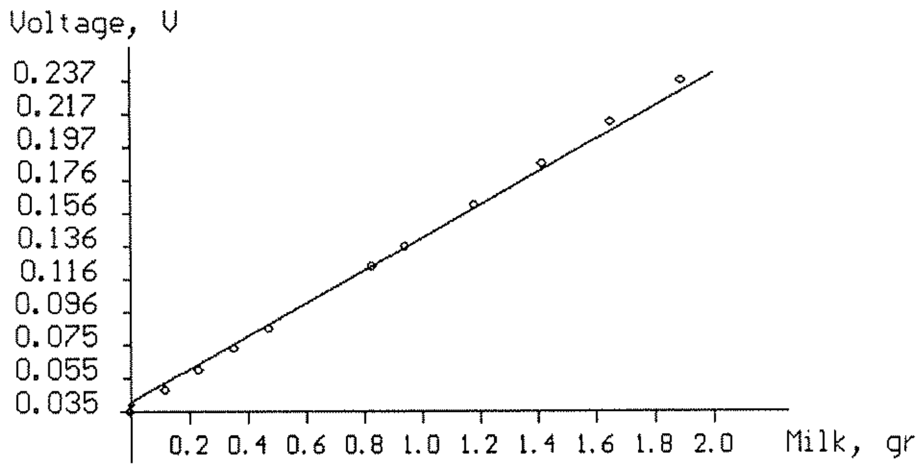
No further additional equipment was introduced.

5.3.4 Calibration

5.3.4.1 Procedures for calibration

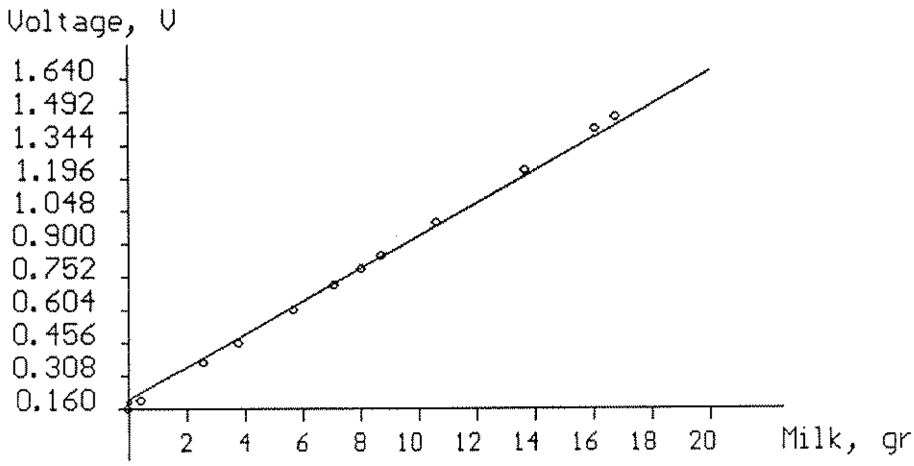
As described in Section 5.2.4.1.

5.3.4.2 Calibration curve



$$Y = -0.0036 + 0.133 \cdot X$$

Figure 32. Calibration curve and equation, low flow rates.



$$Y = 0.16 + 0.074 \cdot X$$

Figure 33. Calibration curve and equation, high flow rates.

5.3.5 Practical procedures

The experimental cows were found to have a strong tendency to milk in an "unnatural" way following a major change in milking routine. Experimental results showed clearly that the cows needed a period to get used to the different milking routines. The experimental cows were therefore milked for three days prior to an experiment using exactly the same procedures applied during the experiment.

During these introductory days the equipment could be tested. The milk level in the regulation cell and the amplification of the regulation could also be adjusted to an optimum level.

5.3.6 Expectations

The tests done in the laboratory were very encouraging. It was found that the measuring range was 2 times higher than before the insertion of the shunt.

5.3.7 Experiences

5.3.7.1 Characteristics of measuring probe

Due to high milk flow and abrupt change of flow direction, scum appeared in the regulation cell. This influenced the regulation of the milk level and thereby had a negative effect on the milk flow measurement. The scum gave rise to two serious problems: a phase displacement between registered milk flow and real milk flow and an unrealistic peak in the registered milk flow rate as depicted in Figure 34 (Mayntz, M., Smårs, S., de Toro, A., Oostra, H. & Ericson, G. 1989). The magnitude of these problems increased with the amount of scum in the regulation cell.

The resistance between the two electrodes in the regulation cell is very small when it is filled with scum and consequently the pump operated all the time to "evacuate" the milk that was not there. This caused too much air to enter the Doppler device, resulting in false milk flow data. An amount of milk, higher than ever an instantaneous flow rate through the streak canal can be, entered the regulation cell when the congested milk in the upper part of the cup finally overcame the foam wall, which also resulted in false flow data. Figure 34 shows very clearly that milk passes the measuring device even during the atmospheric part of the vacuum cycle. Especially cycle numbers 36 to 40 give a good impression of the difficulties related to milk foaming. The milk flow measured during the vacuum phase is very small and irregular. The milk flow rate in the atmospheric phase is greater in magnitude than the real milk flow rate could ever be.

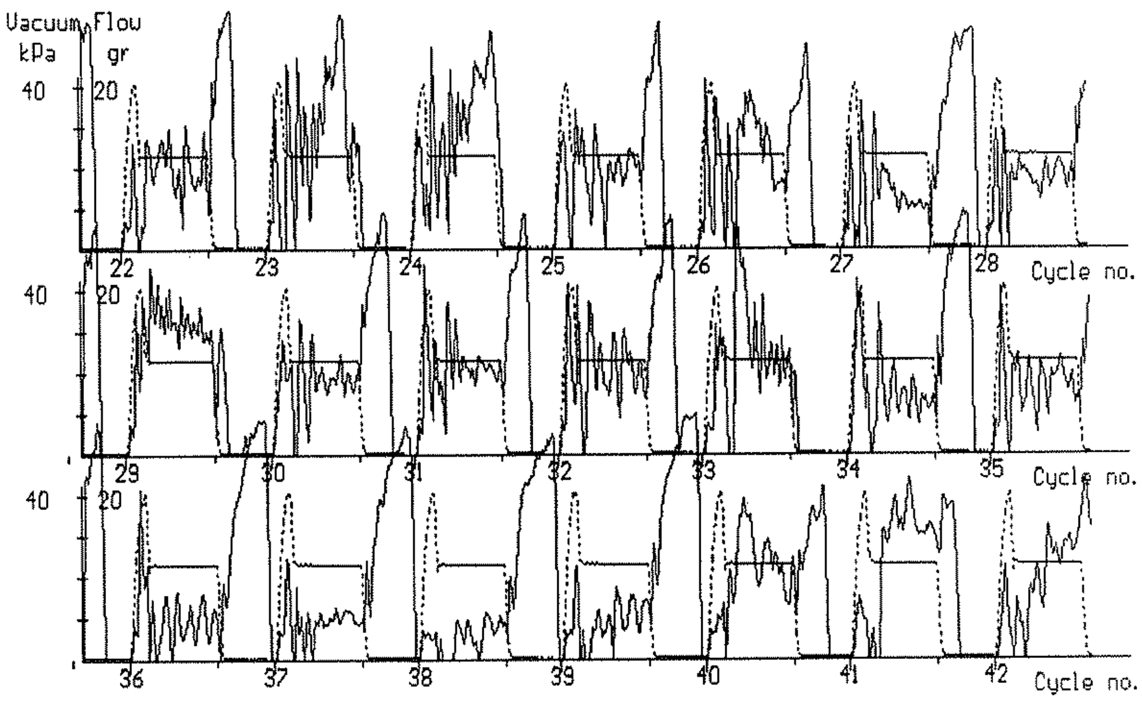


Figure 34. Milk flow pattern with severe phase displacement due to foaming.

Cycles 36, 37, 38 and 39 have even greater peak flows than shown in Figure 34. The computer program drawing the cycles is constructed in such a way that peak flow rates exceeding a certain maximum value are cut off in order to make it easier to read a computer screen full of vacuum and milk cycles. Thus, cycles 36 to 39 have nearly horizontal peak flow rates. The real flow rate values are, of course, saved in the computer's primary memory so that these values are used for evaluation. It must be again emphasized that this material cannot be used for instantaneous milk flow rate measurements. It is even doubtful if it can be used to calculate the mean milk flow rate over an entire cycle.

Unfortunately, this measuring device was not reliable at all and the data obtained varied widely. The data from the device described in Section 5.2.2 had a variation coefficient of 5 % and after shunting the variation coefficient increased to about 50 %. The use of this equipment clearly could not result in reliable data. The only sound idea was to abandon the Doppler principle and to find a new and more reliable method.

5.3.7.2 Further experiences

The cup had become even harder to handle due to the additional parts attached to it.

5.4 Contact-free cup combined with one constriction tube

5.4.1 Description of the experimental teat cup

As described in Section 5.2.1.

5.4.2 Description of the measuring probe

The measuring tube used had to be designed in such a way that the flow pattern before and after the orifice would not be disturbed unnecessarily. Two "flow straightening trajectories" were used, each of them having a length of circa 85 millimetres.

These "flow straightening trajectories" were made of plexiglass tubes with an outward diameter of 20 millimetres and an inward diameter of 16 millimetres. Circa 300 millimetres of a plexiglass tube was placed in a turning lathe. After a period of heating, the lathe was stopped. Then the free end of the plexiglass tube was pulled slowly and carefully. Thus the tube narrowed at its heated end. Pulling was stopped when the diameter was of the same dimension as the flexible milking tubes used. With a bit of luck two "flow straightening trajectories" could be made at the same time.

Between two "flow straightening trajectories" a brass orifice was amounted with a external diameter of 20.6 millimetres and a internal diameter of 3.6 millimetres. However, different orifices were used with different internal diameters in order to obtain varying measurement ranges. A piece of ordinary milk tube was used to join the two "flow straightening trajectories" and the orifice together. Figure 35 explains the measuring probe.

Although no orifice according to standard dimensions was used was it nevertheless significant to avoid elbows, tees, bends, valves, etc., for a certain minimum distance on the upstream side of the orifice. The presence of such disturbances close to the orifice may lead to errors. In order to be certain the same distance was used on the downstream side of the orifice. The minimum distance depends on a β factor, which is the quotient between the orifice diameter and the pipe diameter. With an orifice diameter of 3.6 mm and a pipe diameter of 16 mm the minimum run of straight pipe was 80 mm.

The differential pressure transducer used for measuring the pressure difference over the constriction is discussed in Appendix 3.

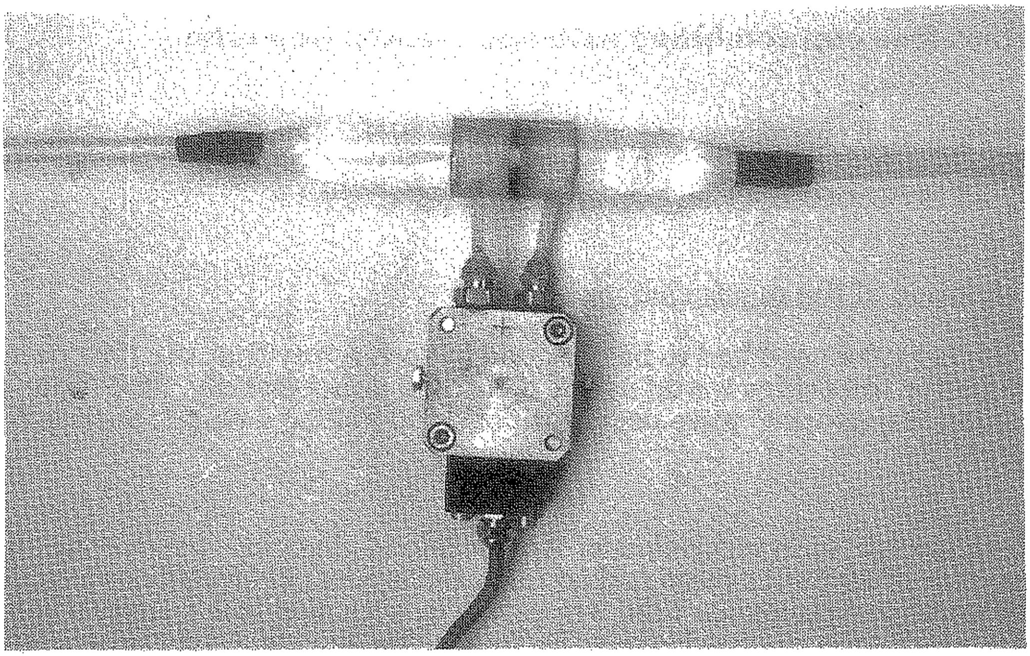


Figure 35. Measuring probe constriction.

5.4.3 Additional equipment

Research showed that the two alcohols nonanol and octanol had a very positive influence on the foaming tendency of milk. Only a very small amount of these fluids was needed to overcome the establishment of foam walls totally. A drip applicator as used in hospitals was used. A constriction in the tube connecting the alcohol bottle and the needle entering the teat cup just above the regulation cell controlled the alcohol flow. This position for the needle was chosen so as to avoid contact between the teat and the needle.

Figure 36 shows the scum control device. The needle on the right of the picture is stuck in the experimental milk cup as depicted in Figure 37. The upper part of the scum control device is stuck into a bottle containing the alcohol by means of a cork, as shown in Figure 38.

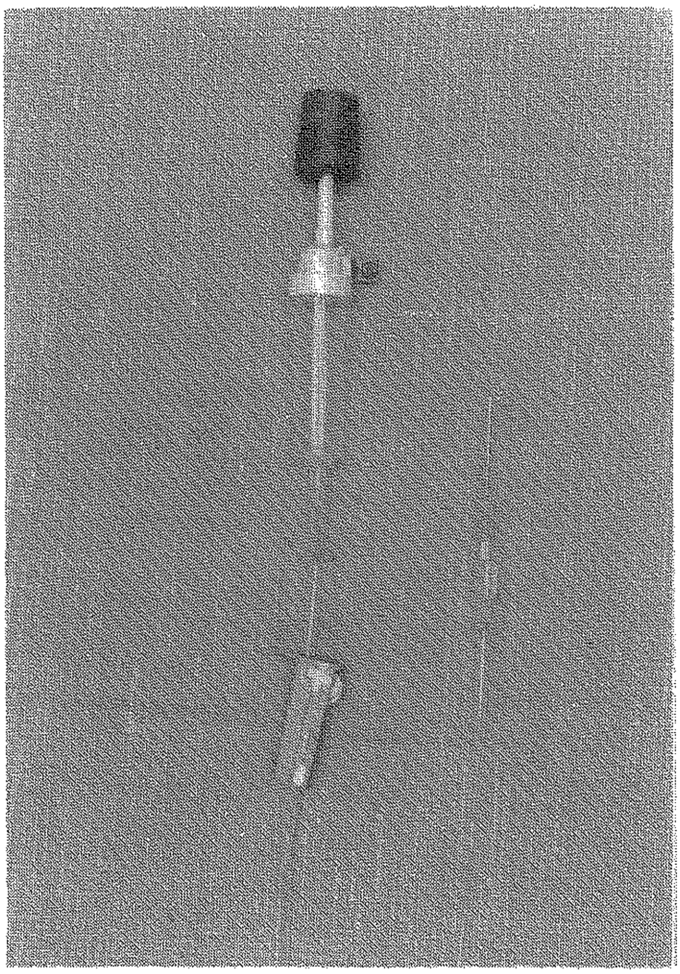


Figure 36. Scum control device.

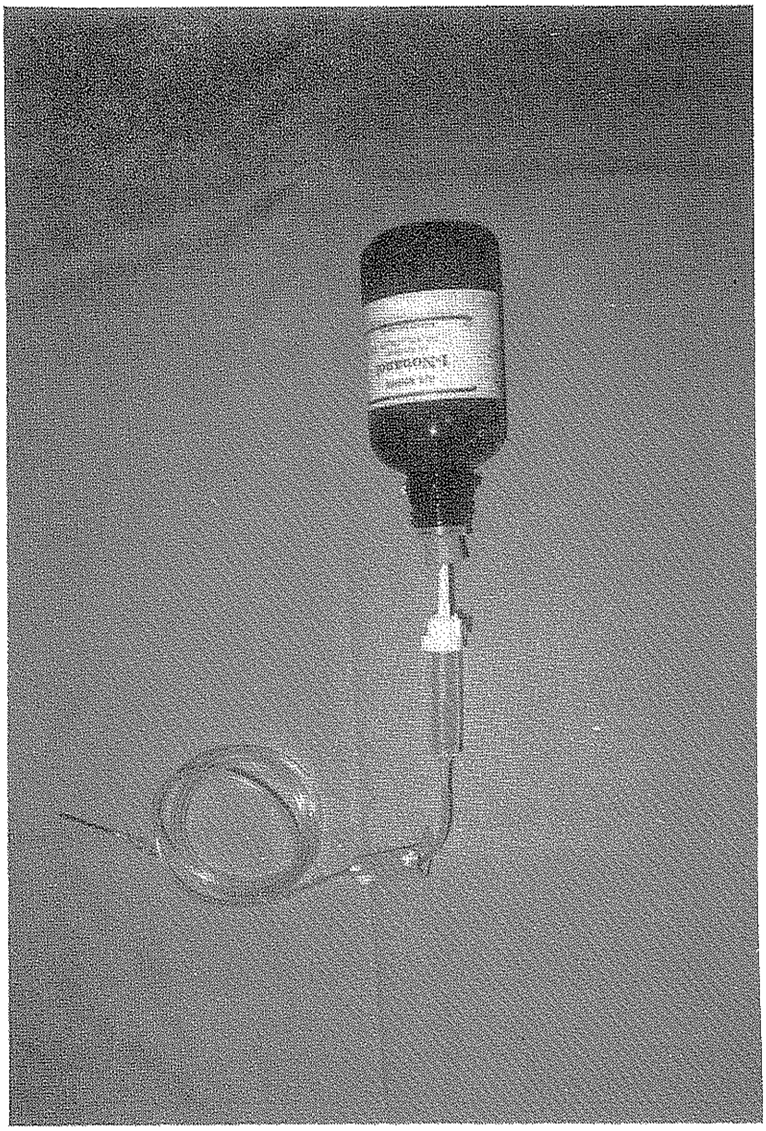


Figure 37. Scum control device and alcohol bottle.

The measuring device was much larger than the previously used Doppler device. A special plexiglass frame had to be built in order to be able to couple the measuring device to the teat cup in a easy way.

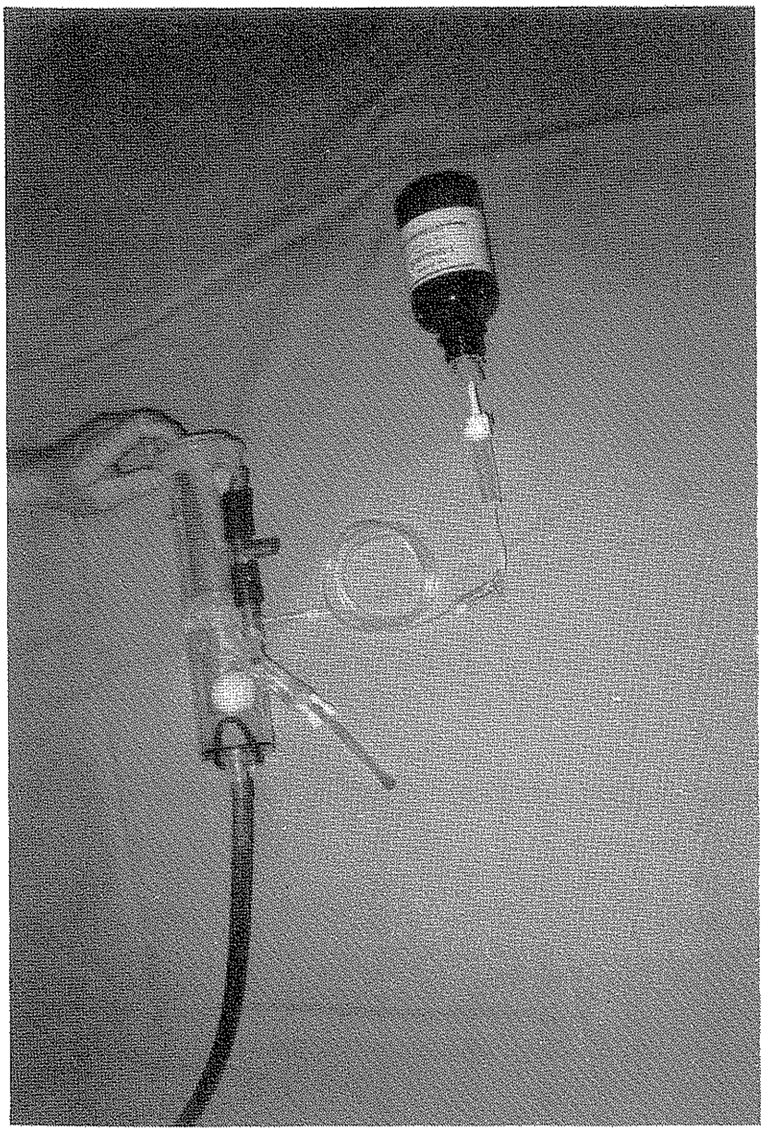


Figure 38. Scum control device mounted on milk cup.

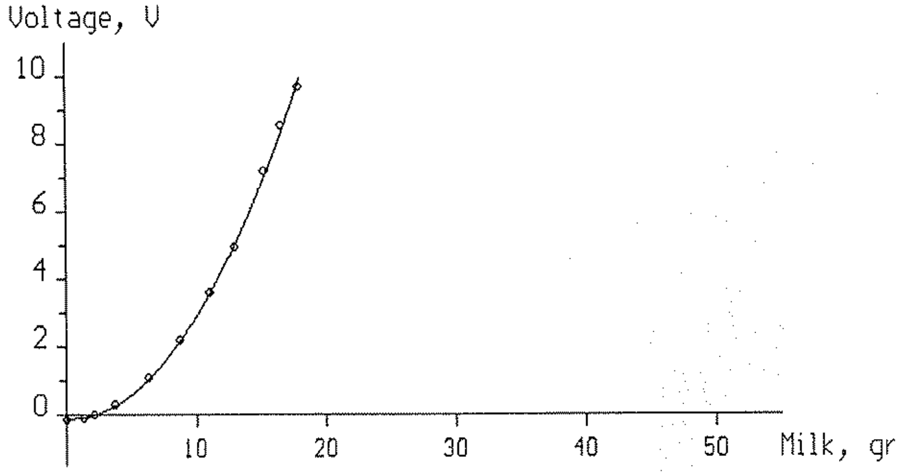
5.4.4 Calibration

5.4.4.1 Procedures for calibration

As described in Section 5.2.4.1

5.4.4.2 Calibration curve

A second degree equation was set up from the calibration data, the small dots in Figure 39 represent the actual measuring data.



$$y = 0.0319 \cdot x^2 - 0.0089 \cdot x - 0.1309$$

Figure 39. Calibration curve and equation for a single constriction measuring probe, valid for milk flow rates between 0 and 20 millilitres per second.

The measuring device is only calibrated for milk flow rates up to 18 millilitres per second.

5.4.5 Practical procedures

The flow of the alcohol into the teat cup was adjusted to one drop per three to four vacuum phases, i.e. 24 to 40 seconds between drops. If the milk flow was very low no alcohol was needed since foaming is correlated to milk flow.

The needle was attached to the cup with a meltable silicon substance in order that the needle could be removed when the cup had to be cleaned.

The tube leading the alcohol to the needle tended to become inflexible after about one week of use, probably due to a chemical change in its material caused by the unusual chemicals. Consequently, we changed the alcohol applicator every week in order to maintain a flexible tube.

5.4.6 Expectations

Since this method had not been tested previously great care had to be exercised when introducing it even though pre-experimental tests were very positive.

5.4.7 Experiences

5.4.7.1 Characteristics of the measuring probe

Figure 40 shows three different vacuum pattern frequencies, cycles 1 to 50 having a frequency of 0.67 Hz, cycles 51 to 75 having a frequency of 0.33 Hz and cycles 76 to 85 having a frequency of 0.22 Hz.

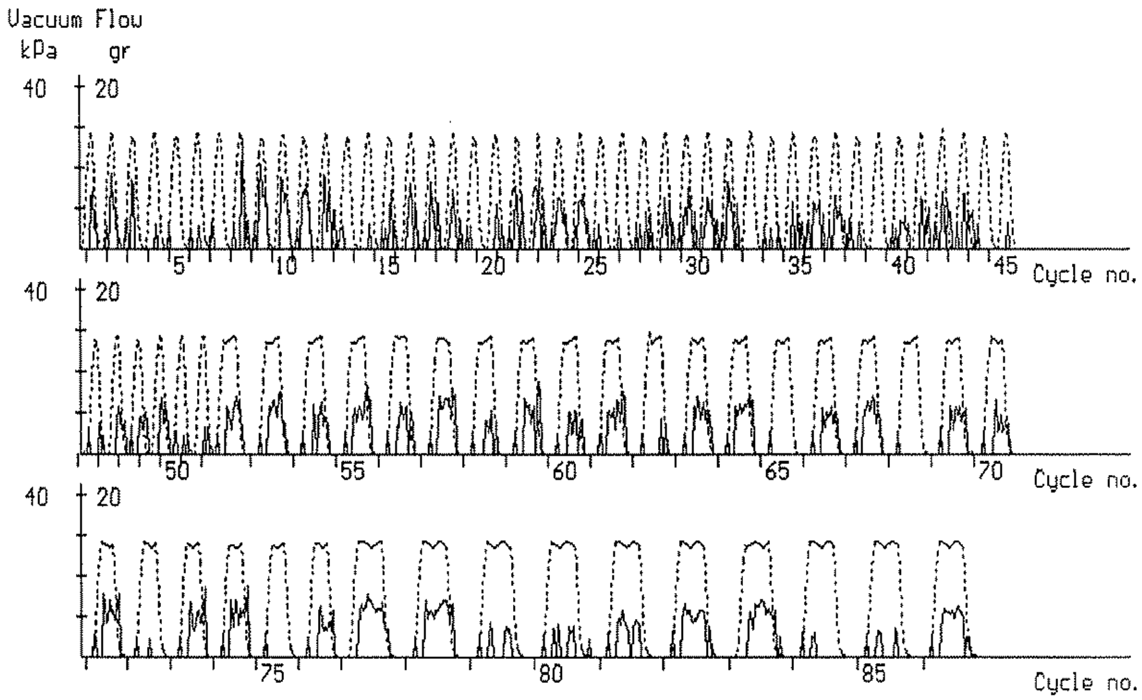


Figure 40. Milk flow profile in combination with vacuum profile.

It may be of interest to compare cycles 1 to 50 in Figure 40 with Figures 4 and 5 in Section 3.2. Clear milk flow rate oscillations can be distinguished. Milk flow cycles 10, 17, 22, 30, 36, 42 and 48 in Figure 40 are all milk flow rate maxima (compare only with those cycles with the same vacuum frequency, i.e. cycles 1 to 50). These cycles represent actual milk flow rate data. A similar milk flow rate behaviour can be found in Figures 4 and 5.

5.4.7.2 Further experiences

The alcohol totally solved the problem of foaming in the regulation cell. When alcohol was added the milk from the experimental teat had to be degraded.

In the theory described in Section 4.3 it was said that the flow rate measured should be higher than the actual one. In theory there is no variable line pressure. Line pressure is defined as the changing pressure in the total measuring system. Due to the different vacuum patterns applied on the experimental teat the line pressure changes constantly during the evacuation phase. Numerous different patterns from ordinary four-corner pulses to complex single peak patterns had been used. It is not possible, in our case, to determine how the changing line pressure actually influences the milk flow measurement.

The reading of the "real" amount of milk in the tube mentioned in Section 5.1.3 was very rough. It was found that the pressure transducer, used for measuring the milk flow rate, changed signal magnitude, not only with changing milk flow rate but also with a changing line vacuum. This meant that the constant term in the calibration equation had to be changed as seen in Figure 42 in Section 5.5.4.2.

It was decided that any future improvement in terms of a better flow measuring probe would not involve attachments to the teat cup in order to save weight and to improve movabilty, see Figure 41. Unfortunately, this results in longer tubes between the teat cup and the measuring probe and phase displacement. This setback was not considered to be a major disadvantage because of the invariable nature of this new phase displacement. The pressure exerted by the pump used was high enough to overcome the increase in flow resistance.

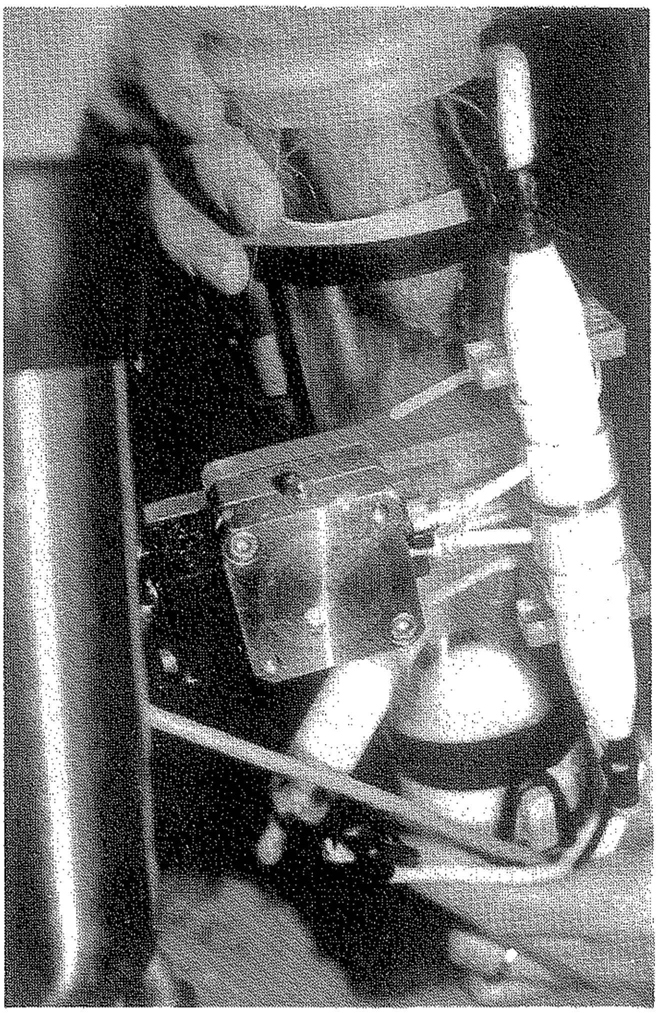


Figure 41. Fully equipped experimental teat cup.

5.5 Contact-free cup combined with one constriction tube helped by two pumps

5.5.1 Description of the experimental teat cup

As described in Section 5.2.1.

5.5.2 Description of the measuring probe

As described in Section 5.4.2.

5.5.3 Additional equipment

The improvement made in this step of development was the use of two identical pumps instead of one. Two pumps coupled in parallel have a different pump characteristic than a single pump.

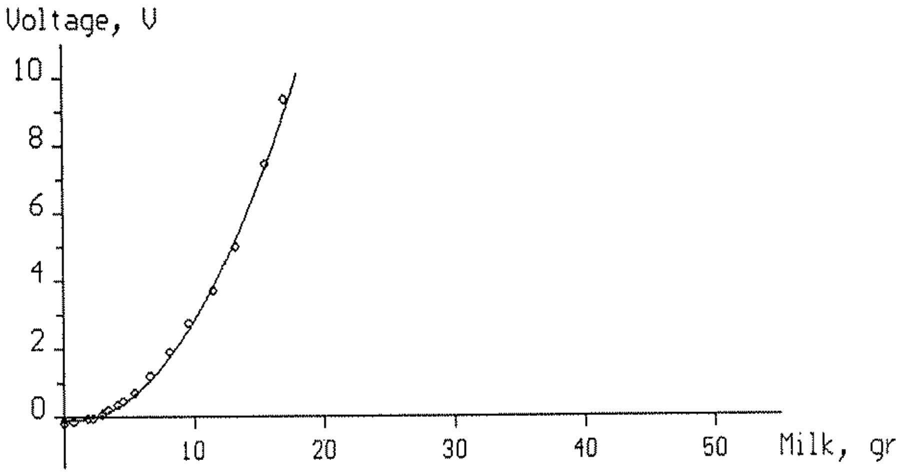
Although not necessary, we changed the transistor which operated the pump in order to be on the safe side. Both pumps use about one ampere at peak rate, where total power consumption is about 24 watts. In our design, the total power required by the motors flows through the transistor and therefore we changed the BD-657-A PNP transistor for a BDX-33-C Darlington NPN transistor. The maximum power tolerated for the 657 is 40 watts for the BDX 70 watts.

5.5.4 Calibration

5.5.4.1 Procedures for calibration

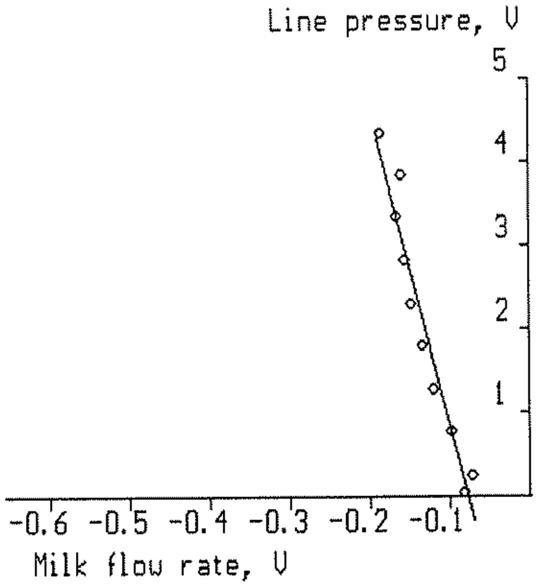
As described in Section 5.2.4.1

5.5.4.2 Calibration curve



$$Y = 0.0344 \cdot X^2 - 0.0474 \cdot X - 0.0856$$

Figure 42. Calibration curve and equation for a single constriction, valid for milk flow rates between 0 and 20 millilitres per second.



$$y = -37.9661 \cdot x - 2.9439$$

Figure 43. Compensation curve and equation for changing line pressure.

5.5.5 Practical procedures

No different procedures were put into practise.

5.5.6 Expectation

Beside a higher pump capacity it was also expected that the system would react faster to any disturbance imposed upon the system.

5.5.7 Experiences

5.5.7.1 Characteristics of the measuring probe

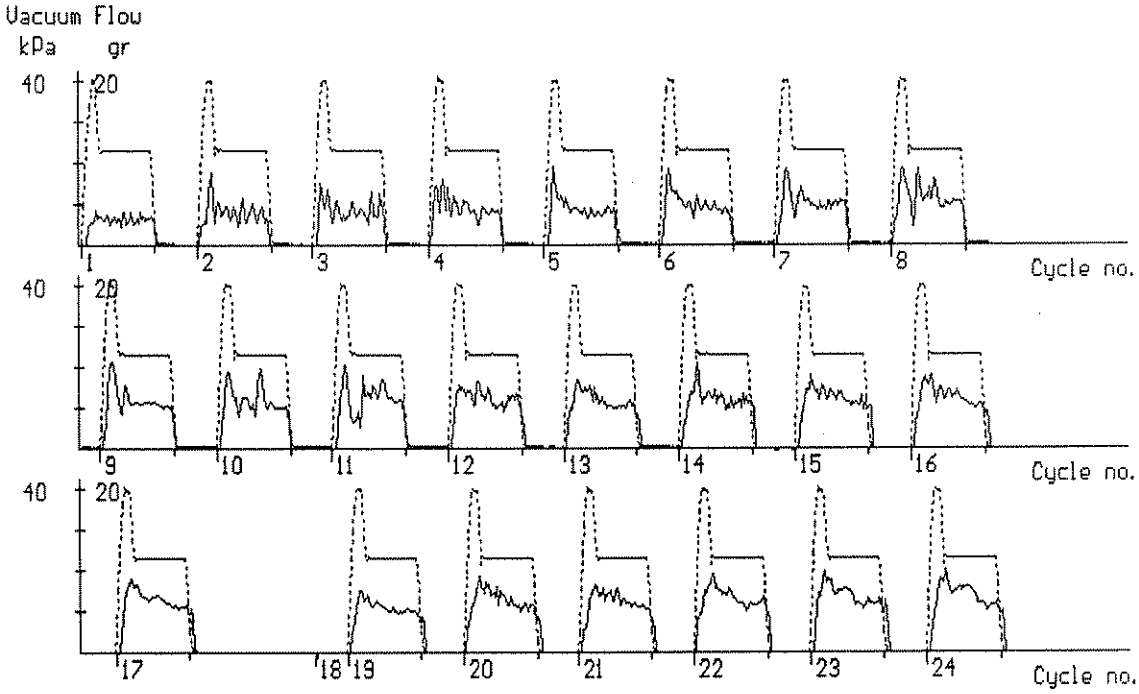


Figure 44. Milk flow profile in combination with the vacuum profile.

5.5.7.2 Further experiences

Unfortunately the two parallel-coupled pumps did not completely come up to expectations. The maximum pump capacity increased to 1.5 times the capacity of a single pump. Although this was not the expected magnitude it was nevertheless an improvement.

We learned from experience that a larger fuse had to be installed for the two pumps.

5.6 Contact-free cup combined with two constriction tubes helped by two pumps

5.6.1 Description of the experimental teat cup

As described in Section 5.2.1

5.6.2 Description of the measuring probe

By using two pumps a higher milk flow rate could be put through the measuring probe. To enlarge the measuring range a second constriction, 2.6 millimetre in diameter, was connected in series with the first one. Both constrictions had different, but overlapping, measurement ranges. A computer program selected which constriction should be used. During low flow the constriction with the small diameter was used and during high flow the constriction with the larger diameter.

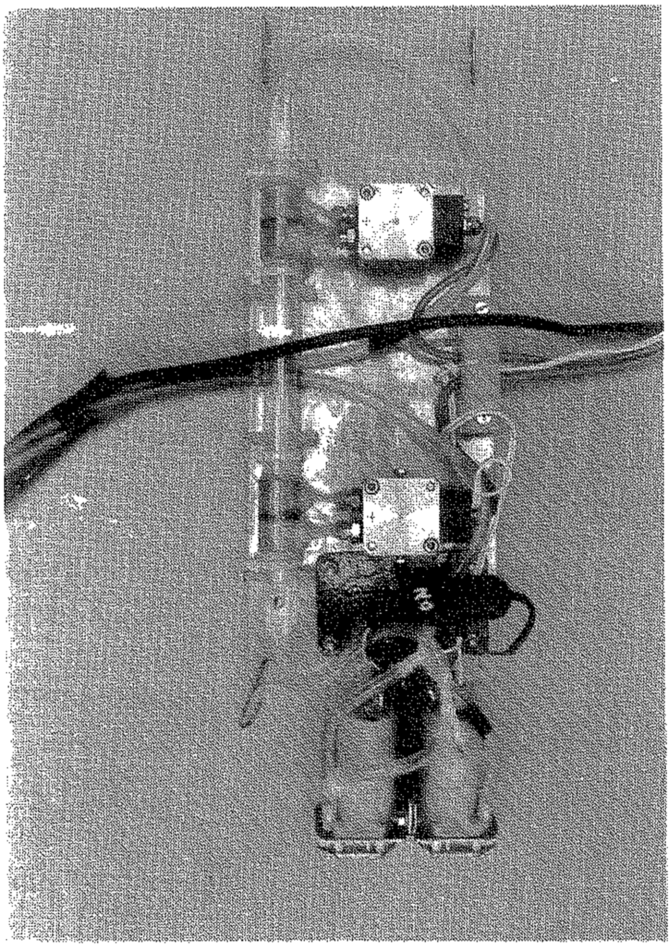


Figure 45. Measuring probe.

The computer used both measuring probes simultaneously, this means that two different files were created when the data were stored. It was a task for data evaluation to decide which file should be read.

5.6.3 Additional equipment

The two pumps and measuring probes were mounted on a plexiglass board that hung on the left side of the lift. It was very important that the measuring probes were located in a vertical position. The gasses dissolved in the milk would otherwise be released and cause serious faults, since they can interrupt the fluid connection between the constriction and the pressure transducer. The dissolved gasses are able to follow the milk stream through the measure probe without causing any harm when the flow probe is mounted vertically.

Since gear driven pumps are very sensitive to impurities we installed a small filter in order to protect the motor. Even small pieces of straw can stop the pump from rotating.

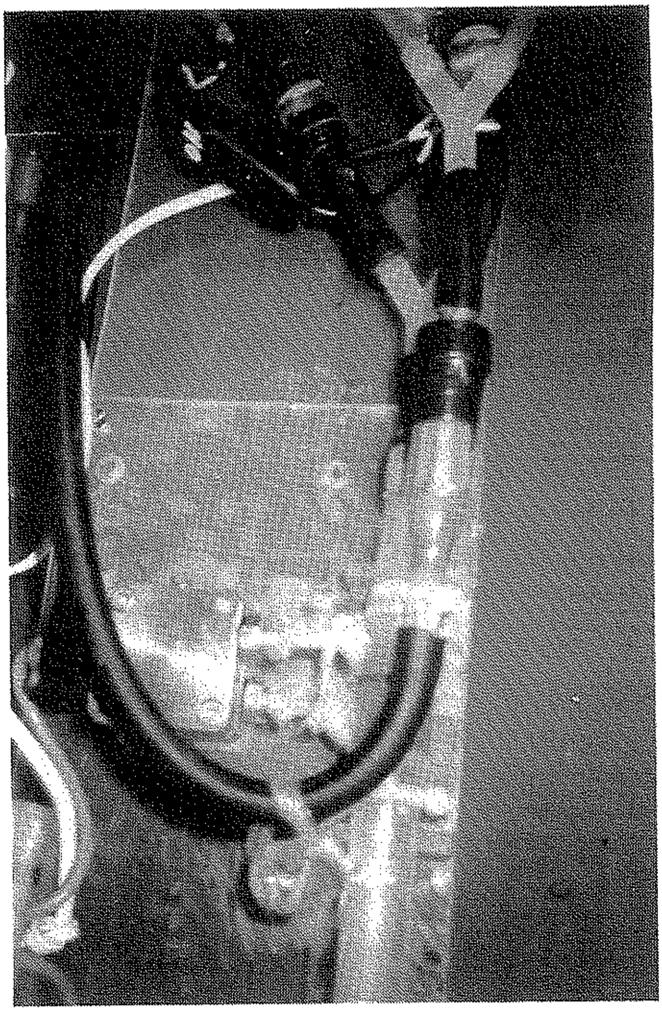


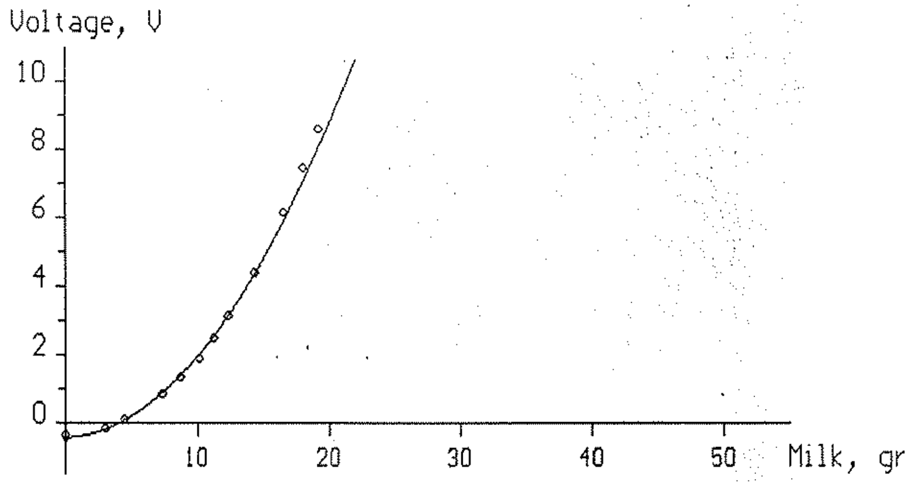
Figure 46. Milk fliter.

5.6.4 Calibration

5.6.4.1 Procedures for calibration

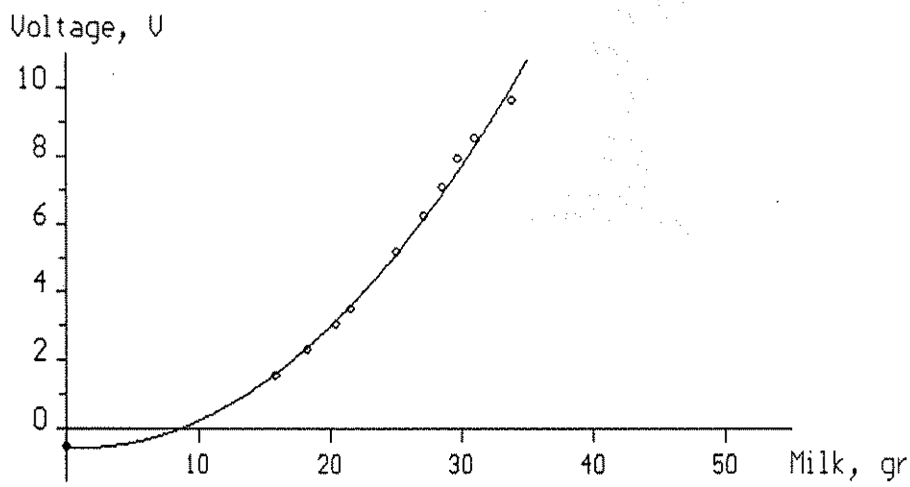
As described in Section 5.2.4.1

5.6.4.2 Calibration curve



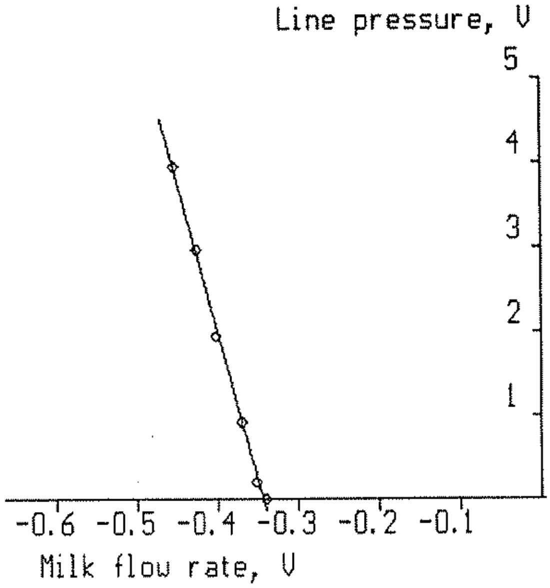
$$y = 0.0220 \quad x^2 + 0.0254 \cdot x - 0.4351$$

Figure 47. Calibration curve and equation, low flow rates.



$$y = 0.0099 \cdot x^2 - 0.0201 \cdot x - 0.5353$$

Figure 48. Calibration curve and equation, high flow rates.



$$y = -35.6296 \cdot x - 12.2487$$

Figure 49. Calibration curve and equation for changing line pressure.

5.6.5 Practical procedures

No different procedures were put into practise.

5.6.6 Expectations

The measuring probe described in Section 5.5.2 functioned very well. The only disadvantage was its limited measuring range. This should not be a problem with the improved design.

The material of the tubes connecting the teat cup to the measuring probes was changed from narrow transparent plastic to the wider, longer, vacuum tubes used in conventional milking equipment.

We always tried to minimize the volume of milk that has to be accelerated and retarded by using tubes that are as short and with as small diameters as possible. However, the new tubes had a lower flow resistance than the previous ones. This is not only due to the change in diameter, because plastic tubes with a similar inner diameter revealed a higher flow resistance.

So not only the relation of volume and diameter but also the resistance of the material has to be optimized. This problem was not studied further since the phase displacement did not increase after the installation of the new tubes, at least not to an extent measurable with our equipment.

5.6.7 Experiences

5.6.7.1 Characteristics of measuring probe

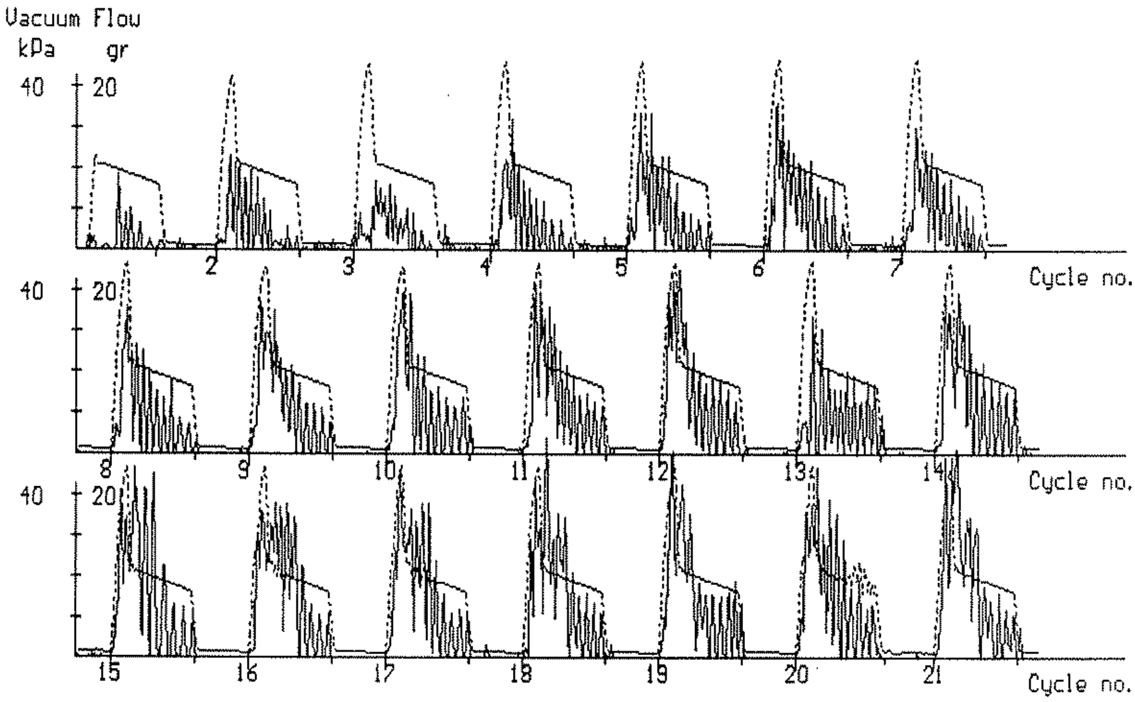


Figure 50. Milk flow profile in combination with the vacuum profile.

5.6.7.2 Further experiences

The total height of the plexiglass teat cup was 290 mm, and when fully equipped its weight was circa 900 grams, excluding the small volume of milk in the lower chamber of the milk cup. As both the measurement device and the pumps were removed from the teat cup the tubes became longer and longer. The risk of a kick from a cow increases when the number and length of the tubes increases. Therefore it was now decided to develop a new cup with a minimum number of tubes connecting the cup with the additional equipment and with the measuring probe. This means at least four tubes; for pressure measurement, for vacuum application, for adding alcohol and, finally, for the evacuation of milk from the teat cup. But the new cup had also to be designed in such a way that the milk would flow as gently as possible into the regulation cell in order to be able to solve the foaming problem even without regular addition of alcohol.

In our case it was not possible to construct such a cup of plexiglass and instead we choose to use glass as construction material. A local glassblower made the new cup, described in the next chapter.

5.7 Contact-free glass cup

5.7.1 Description of the experimental teat cup

The latest version of our experimental teat cup can be compared with the upper part of the previous cup. This cup consists of one part to collect milk, applying vacuum to the teat, collecting milk, and also of the regulation cell. All other parts of the former teat cup have been removed and placed elsewhere.

The cup itself was made of glass. The glassblower equipped the teat cup with one inlet for the air tube and two small openings one for the pressure transducer and one for adding alcohol.

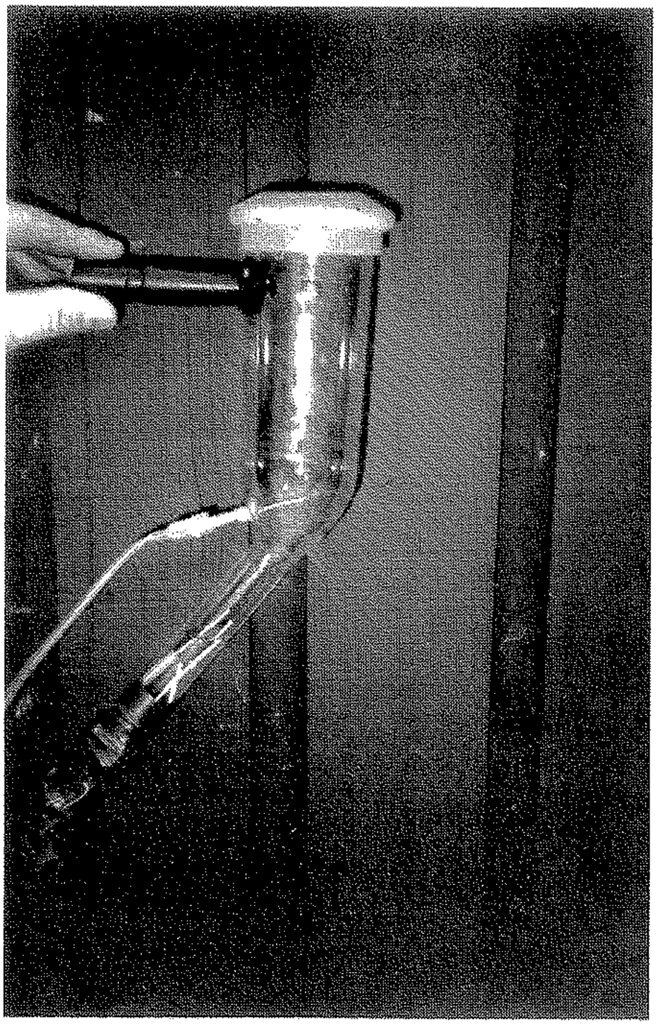


Figure 51. Contact-free glass cup.

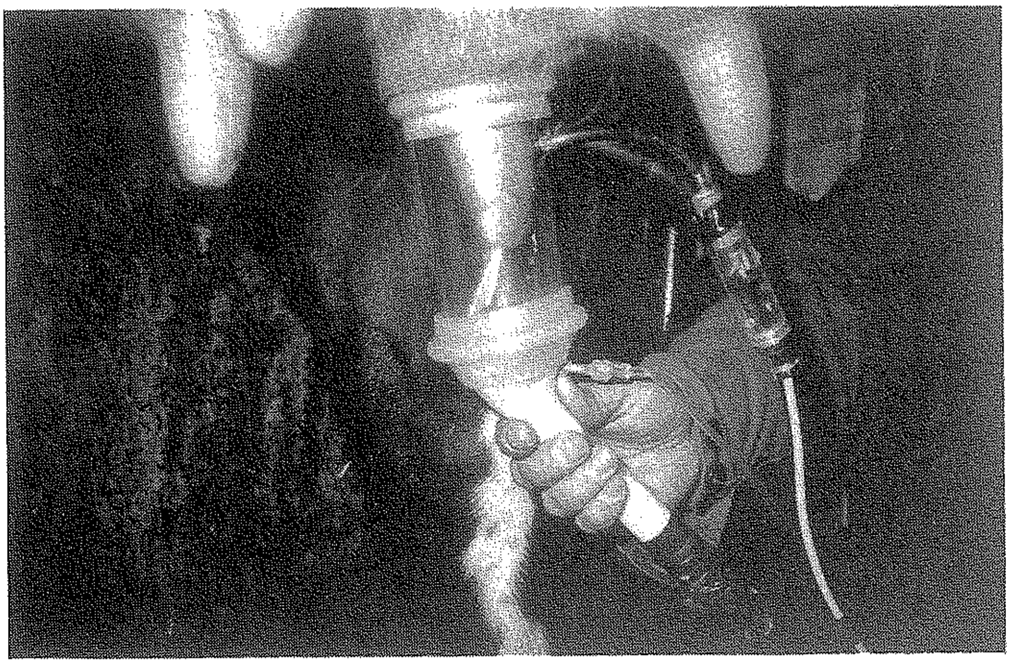


Figure 52. Fully equipped contact-free glass cup.

5.7.2 Description of the measuring probe

As described in Section 5.6.2.

5.7.3 Additional equipment

A single tube connects the upper chamber with the lower chamber, creating a very compact teat cup. The lower chamber, from now on referred to as the "float cup", is placed on a stand just beside the milker. The float cup had to be placed at a higher level than the milk cup, otherwise the regulation cell and the measuring probe would be drained of milk. The tube connecting the glass teat cup with the float cup is provided with a non-return valve, which is necessary in order to prevent the pumps from running constantly.

It was still necessary that there was no pressure difference over the measure probes and the pumps. This means that once the milk has flowed through the measuring probes, it must be collected in a container with exactly the same pressure as in the teat cup itself. This means a similar arrangement as described in Section 5.1.

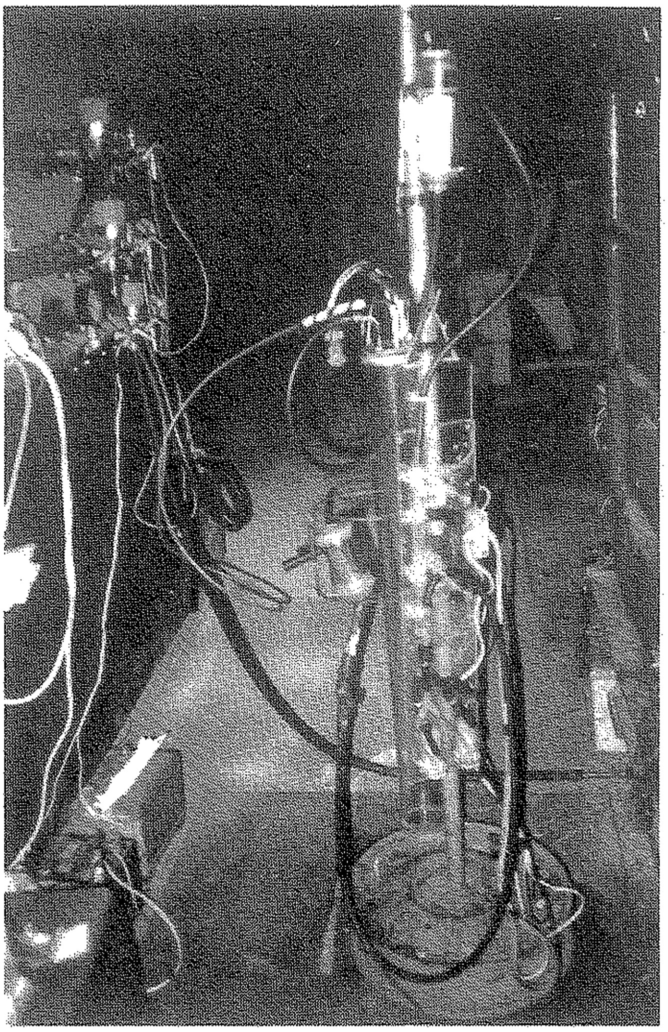


Figure 53. Float cup and other milk measurement equipment.

5.7.4 Calibration

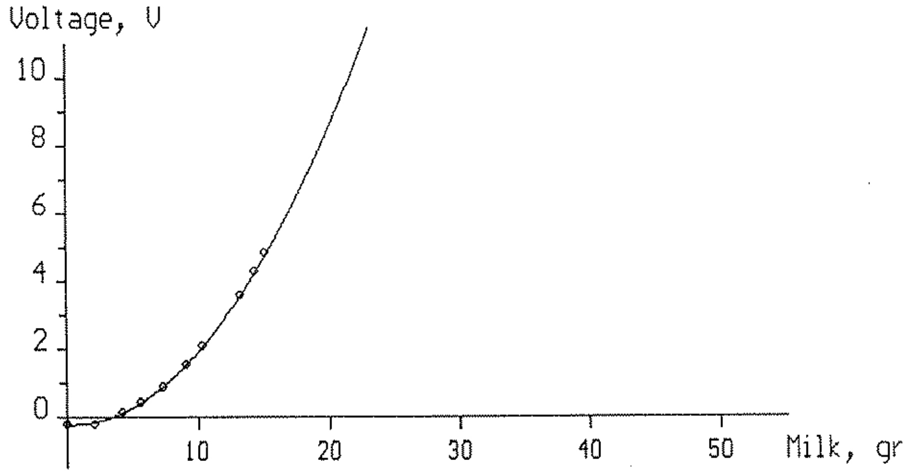
5.7.4.1 Procedures for calibration

As described in Section 5.2.4.1

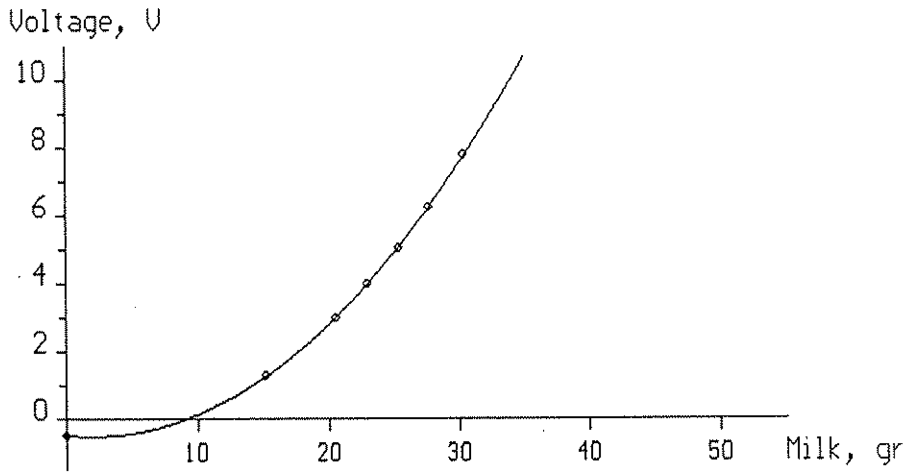
5.7.4.2 Calibration curve

The curve in Figure 54 is valid for milk flow rates between 0 and 15 grams per second, although the curve is interpolated for values up to 22 grams per second. Figure 55 is used for milk flow rates between 15 and 30 grams per second.

Figure 54. Calibration curve and equation, low milk flow rate.

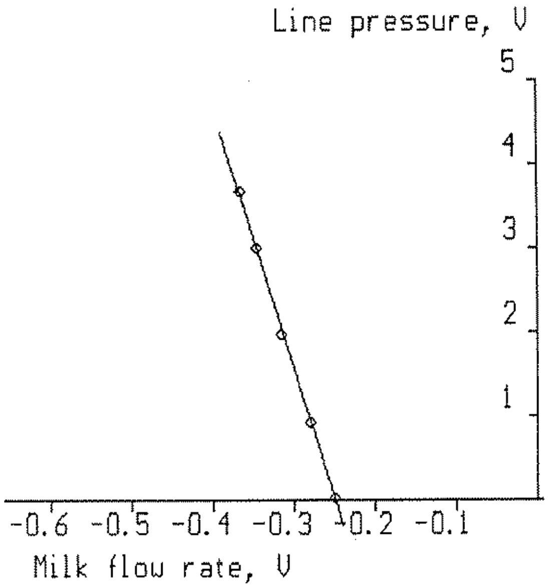


$$Y = 0.0227 \cdot x^2 - 0.0096 \cdot x - 0.2270$$



$$Y = 0.0103 \cdot x^2 - 0.0387 \cdot x - 0.5016$$

Figure 55. Calibration curve and equation, high milk flow rate.



$$y = -31.1139 \cdot x - 7.7630$$

Figure 56. Calibration curve and equation for changing line pressure.

5.7.5 Practical procedures

Previously, the teat cup and the measuring probe were cleaned separately. This procedure was now abandoned. The teat cup and measuring probe were from now on normally not disconnected during an experiment. A random inspection of the pressure transducers revealed, however, that they had become filled with a cheese-like substance. Therefore, after each milking, the transducers were opened during cleaning and rinsed, not being closed until clear water flowed out of the opening.

5.7.6 Expectations

The new experimental teat cup was very well made. Its construction provided a smooth change between the part of the cup functioning as collecting part and the regulation cell. As a result, the tendency to foam diminished and the cleaning was much easier. The usage also improved, partly due to the removal of the measuring device but also because the teat cup was very compact, making it much easier to manoeuvre. The choice of material may seem inconvenient as glass is not normally a material suitable for devices used under rough conditions. But this special choice of material made it possible to construct the teat cup in a very special way which would not have been possible if plexiglass had been used. Now the entire teat cup could be constructed in one piece.

5.7.7 Experiences

5.7.7.1 Characteristics of the measuring probe

Figure 57 shows a flow pattern that has a small phase displacement. The phase displacement varies slightly between the different phases due to an air bubble between the experimental teat cup and the measuring probe. The air bubble has its origin in three different things. Firstly, the flow velocity decreases just before the filter; secondly, the tube connecting the experimental cup with the measuring device is curved; and thirdly, the air bubble cannot pass the filter.

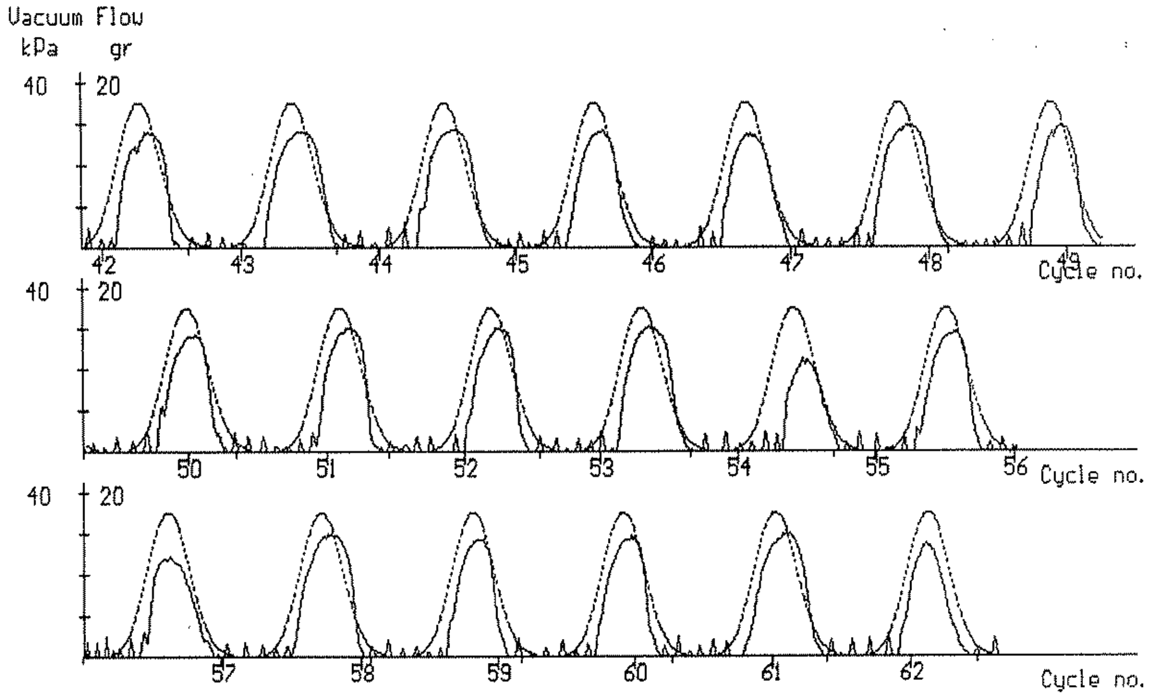


Figure 57. Milk flow profile with irregular phase displacement.

5.7.7.2 Further experiences

Despite being made of glass the cup showed great resistance to mechanical strain. The plexiglass cup had to be repaired several times, and up to now no such repairs to the glass cup have been necessary. On the other hand, any eventual changes to its design will need professional help.

Hitherto, the control of the milk level in the regulation cell has been based upon small changes in resistance between the two electrodes caused by minor changes in milk level. This type of regulation is very sensitive to changes in milk resistance. This results in the milk level in the regulation cell being adjusted to different levels when the milk resistance changes. Consequently, the amplification is changed because of the close relationship between milk level and amplification. Obviously one cannot measure accurately when the amplification changes constantly. Constant amplification is one of the major parameters that are indispensable for high measuring accuracy. Therefore, a moderate change in the electronic circuit was made so that the system would be insensitive to any change in milk resistance.

The form of the glass teat cup was later found to be ergonomically designed which improved the comfort in milking considerably.

5.8 Contact-free glass cup with compensation for milk resistance variations

5.8.1 Description of the experimental teat cup

As described in Section 5.7.1.

5.8.2 Description of the measuring probe

As described in Section 5.6.2.

5.8.3 Additional equipment

Initially one of the pumps was equipped with a switch so that it could be switched off at low milk flows. Each pump was equipped with a non-return valve in order to stop milk from circulating between the two pumps if one of them was switched off. Although it was not directly observed, it might have been possible that milk had been circulating when both pumps were running. A filter was introduced after several fuses had been blown. This was not done earlier because we thought that it would increase the phase displacement but after testing the change it was found to be unimportant for the measuring quality.

A new regulation system, insensitive to changes in milk resistance, had to be developed. The electronic circuit used for the previous regulation could fortunately be used to a large extent.

The previous regulation system was based upon measuring resistance but a system that compensates for changing resistance, for example with a Wheatstone bridge or an electronic divider, can be designed. All these methods have some negative drawbacks. The Wheatstone bridge is sensitive to changes in temperature, meaning that an additional bridge has to be installed for compensation. Using an electronic divider means redesigning the electronic circuit to such an extent that the existing regulation system can no longer be used. Our solution is based upon the use of a potential difference.

Two electrodes, mounted in the regulation cell, were connected to an oscillator. The potential difference created an electric field between the two electrodes. A third electrode, the measuring electrode, is also mounted in the regulation cell just above one of the electrodes that generate the electric field, as seen in Figure 58.

The electric potential generated in the measuring electrode depends only on the milk level in the regulation cell. A rising milk level results in an increase in electric potential. This signal is then used in the same way as in the resistance measurement. The electronic circuit is shown in Appendix 2.

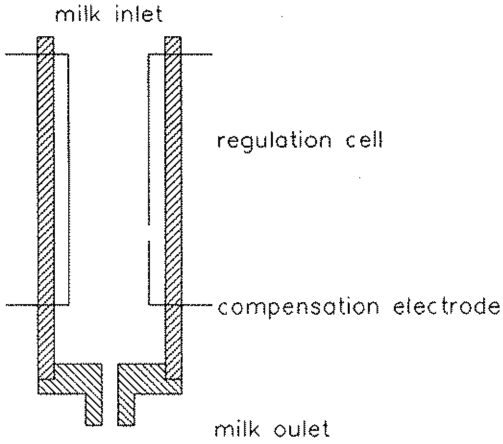


Figure 58. Regulation cell with compensation electrode.

5.8.4 Calibration

5.8.4.1 Procedures for calibration

As described in Section 5.2.4.1.

5.8.4.2 Calibration curve

As depicted in Section 5.7.4.2.

5.8.5 Practical procedures

No different procedures were put into practise.

5.8.6 Expectations

Laboratory tests proved to be very successful.

Unfortunately the system had to be used without careful testing under practical conditions. But the previous regulation system was mounted in standby position as a precaution against failure of the potential difference regulation system. A switch on the electronic circuit made it possible to use either type of regulation system during an experiment.

5.8.7 Experiences

5.8.7.1 Characteristics of measuring probe

Figures 59 and 60 are taken from the same experiment; Figure 59 from the beginning of a milk session and Figure 60 from somewhere in the middle. It can clearly be seen that there is no phase displacement, as depicted in Figure 59.

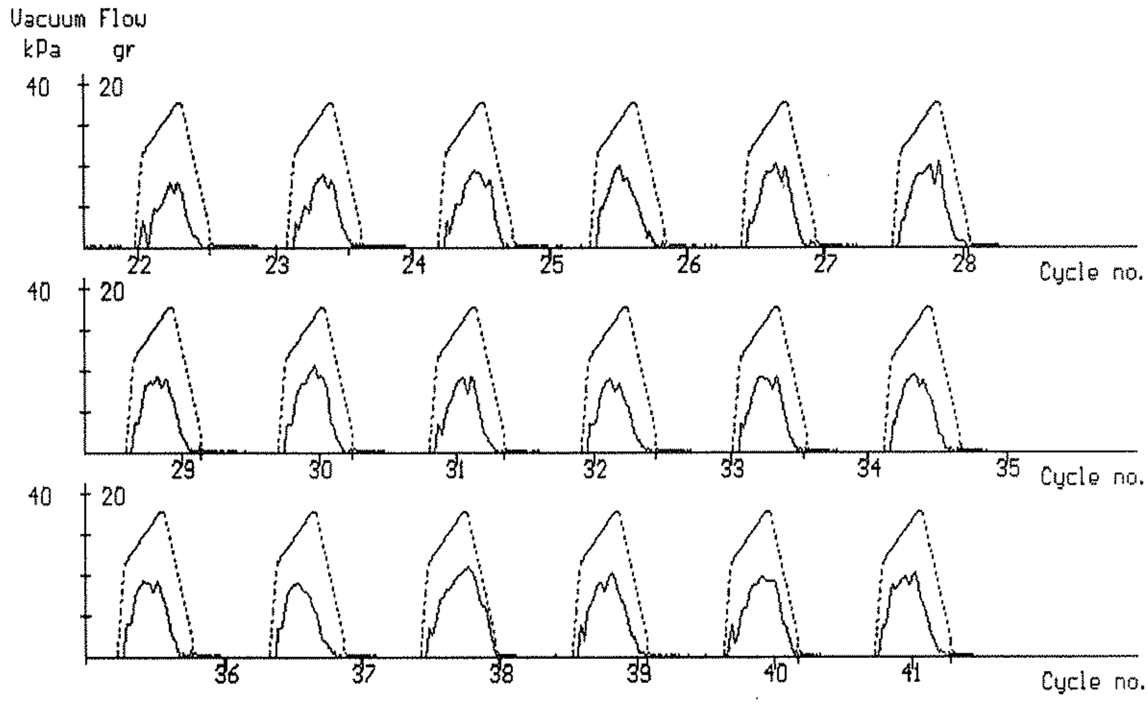


Figure 59. Milk flow at the start of the milking session.

The reason for this phenomenon is explained in the next Section.

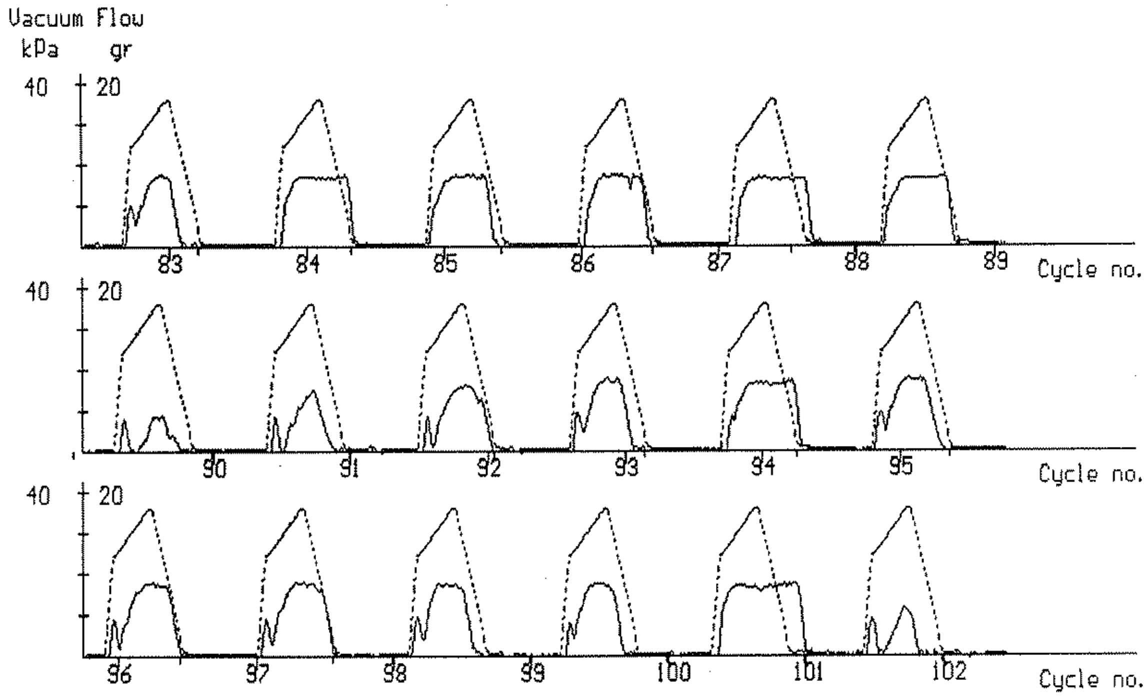


Figure 60. Milk flow in the middle of the milking session.

5.8.7.2 Further experiences

The filter mounted between the teat cup and the measuring probe functioned very well. It filtered out all the impurities, mostly small pieces of straw, that otherwise would have blocked the pumps. The filter, however, gave rise to a large air bubble just before it, which resulted in an unstable milk level in the regulation cell. This was the reason why the improved regulation system did not work as intended.

A solution to this problem has been found, although it has not been tested in practice. We discovered that the air bubble occurred just before the filter. A minor modification to the design of the filter and a different way of mounting it in the milk tubes is expected to be enough for a satisfactory solution. Figures 61 and 62 show schematically the design of the filter and its location before and after the improvement.

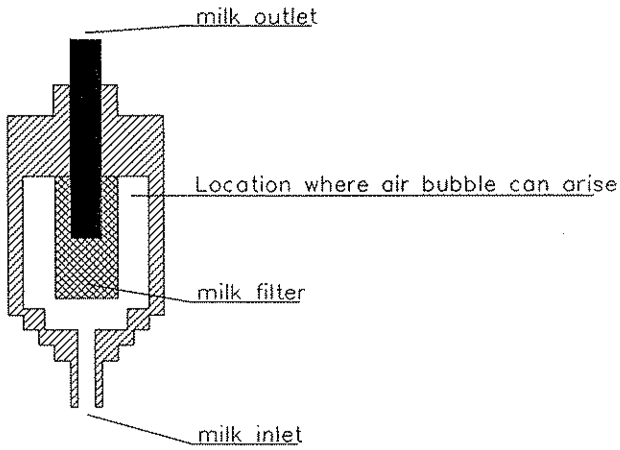


Figure 61. Design of the milk filter before improvement.

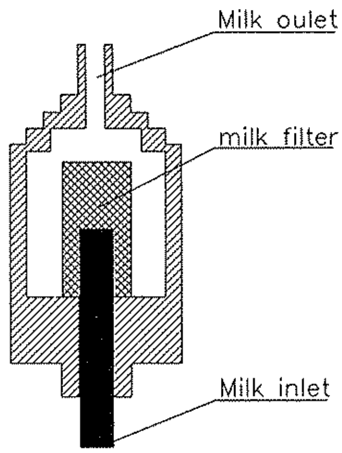


Figure 62. Design of the milk filter after improvement.

This improvement of the milk filter has not yet been tested under practical conditions and consequently there must be some reservations as to its actual performance.

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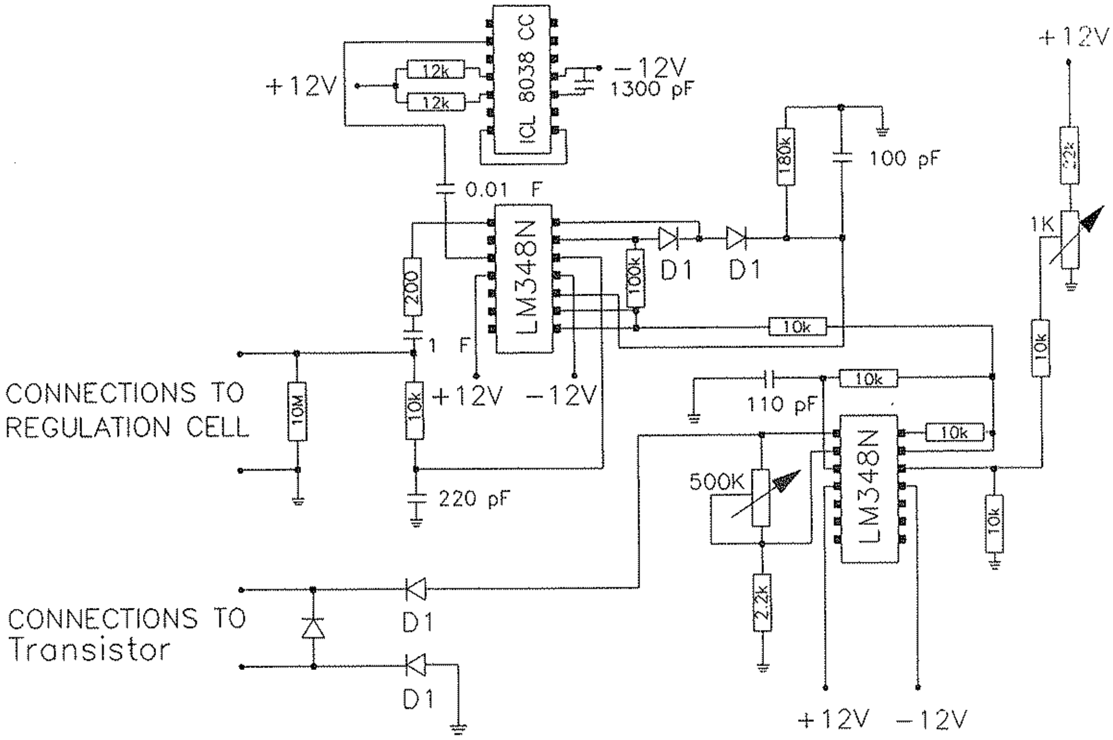
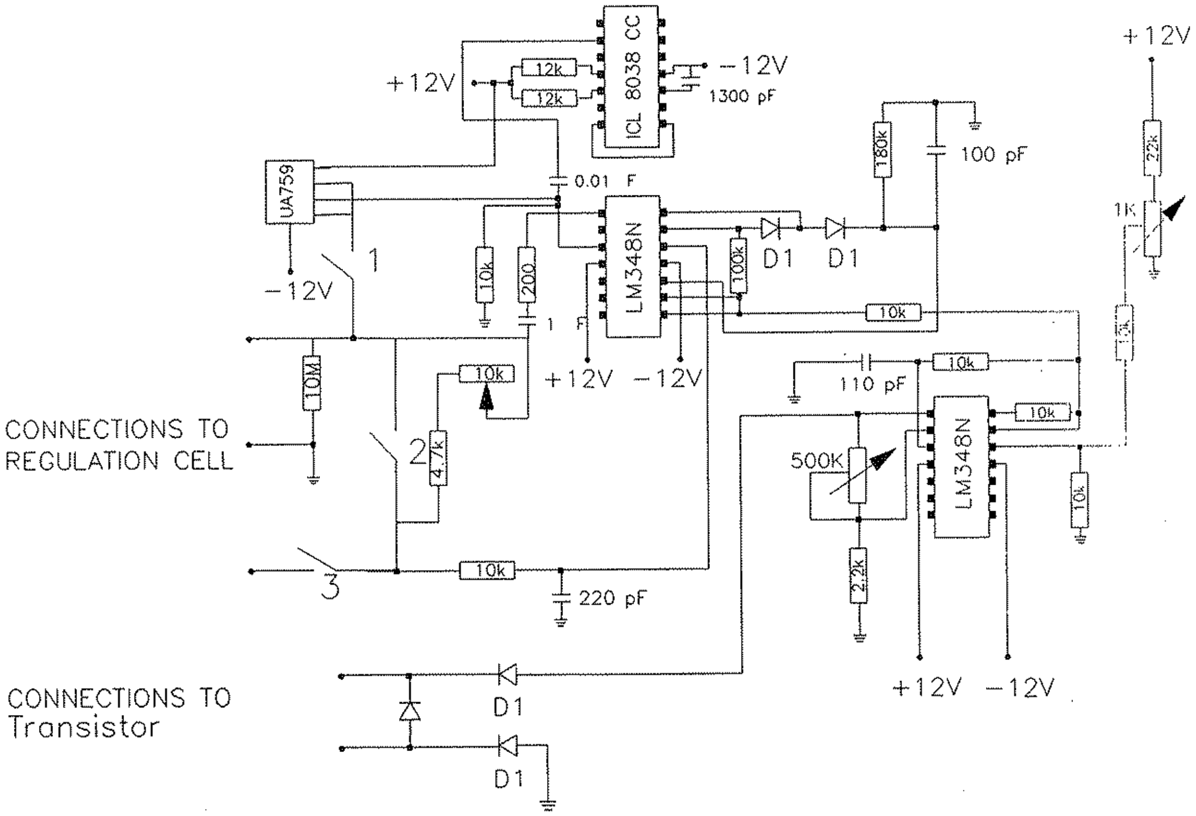
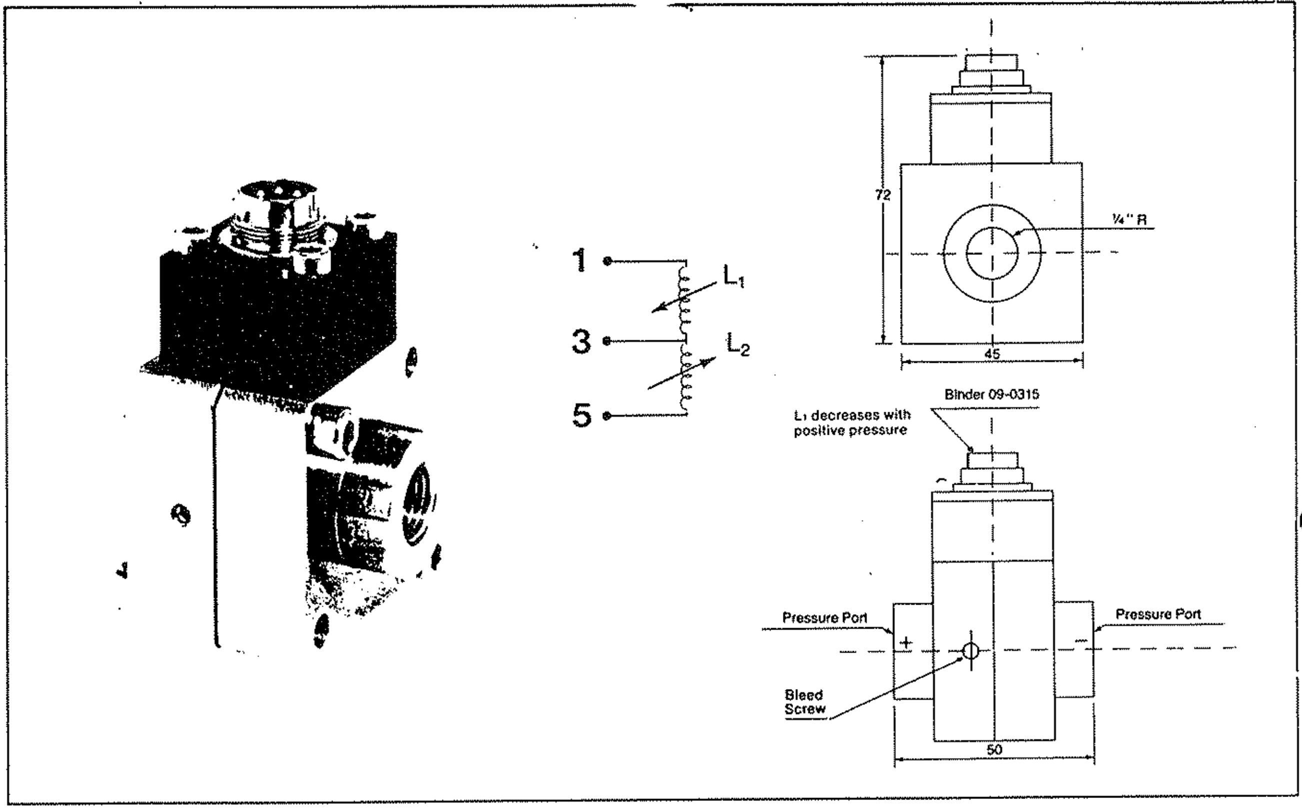

ICL 8038 CC
12k
12k
+12V
-12V
1300 pF
0.01 F
LM348N
D1
D1
180k
100 pF
100k
10k
200
1 F
CONNECTIONS TO
REGULATION CELL
10M
10k
+12V
-12V
220 pF
+12V
22k
1K
10k
110 pF
10k
10k
500K
LM348N
10k
2.2k
CONNECTIONS TO
Transistor
D1
D1
+12V
-12V



3 electrodes	switch 1 ON	switch 2 OFF	switch 3 ON
2 electrodes	switch 1 OFF	switch 2 ON	switch 3 OFF

DIFFERENTIAL PRESSURE TRANSDUCER TYPE PD



DESCRIPTION

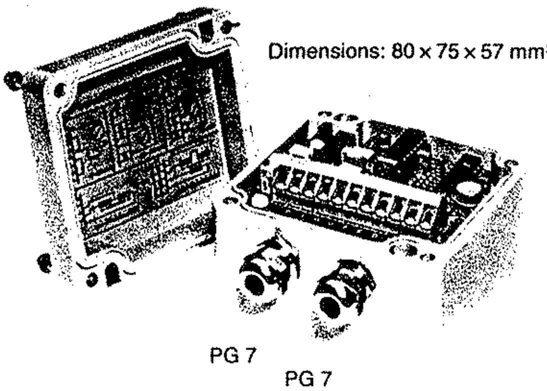
The pressure sensing element is a flat diaphragm of magnetically permeable stainless steel, clamped between two symmetrical assemblies of the same material. The diaphragm deflection is sensed by two coils embedded in the case halves. For dynamic measurement vent valves facilitate complete liquid filling.

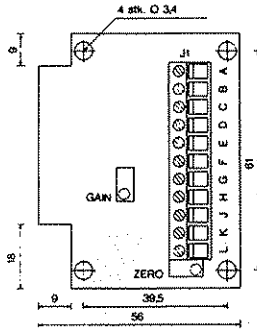
The magnetic reluctance varies with the air gap, changing the inductance ratio. This can be measured in conjunction with the following HFJ Carrier-Demodulators: UCA-5, Mini MCA or MCA 116.

SPECIFICATIONS

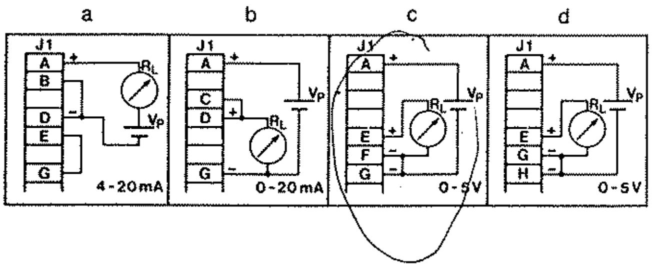
Standard range	:	±50 mbar, ±100 mbar, ±200 mbar, ±500 mbar, ±1 bar, ±2 bar, ±5 bar, ±10 bar
Non-linearity and hysteresis	:	<±0,5 %
Overpressure	:	20 times rated pressure without damage
Line pressure	:	~~200~~ bar max 100
Output	:	25 mV/V full scale nominal
Inductance	:	20 mH each coil
Excitation	:	Rated : 5 V_{rms}, 5 kHz Limits : 1 kHz to 20 kHz
Pressure media	:	Corrosive liquids and gases both sides, compatible with AISI 420
Temperature	:	Operating : −25 to +100°C Compensated : 0 to +75°C
Temperature coefficient of sensitivity	:	< 0.05 %/°C
Temperature coefficient of zeropoint	:	< 0.03 %/°C/FS
Pressure Cavity volume	:	0.35 cm^3
Volumetric displacement	:	0.03 cm^3
Pressure connection	:	¼" R
Electrical connection	:	Binder 09-0315
Weight	:	0.7 kg

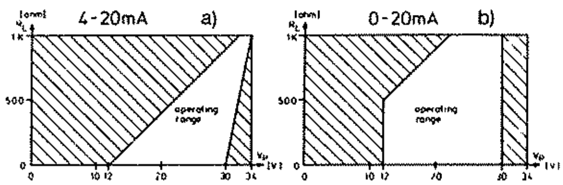
UNIVERSAL CARRIER AMPLIFIER UCA 5





J1-connections
A: Power supply
B: 4–20 mA jumper
C: 0–20 mA jumper
D: Current output signal
E: Voltage output signal
F: 0–5 V jumper
G: 0 Volt
H: 0 Volt
I: Input signal
K: Excitation voltage (+Vb)
L: Excitation voltage (–Vb)





DESCRIPTION

The carrier demodulator type UCA 5 is used with resistive, inductive or capacitive transducers in halfbridge configurations. The amplifier with transducer can function either as a 4–20 mA 2-wire transmitter or as a measuring system with current or voltage output – 3 or 4 wires. The amplifier also features ZERO and GAIN adjustments. The board is provided with screwterminals and can be placed in a tight housing – class IP 65 – with cable entries.

SPECIFICATIONS

Power requirements (Vp)	:	12–30 VDC.
Supply voltage effect	:	<0.1% on output between 12 and 30 V.
Supply current	:	a) 20 mADC; b) 24 mADC; c) 6 mADC; d) 40 mADC.
Carrier frequency	:	nom. 5 KHz ±10%.
Excitation voltage, max.	:	a) 1 V_{rms}; b, c and d) 4 V_{rms}.
Excitation current, max.	:	a) 0.5 mA_{rms}; b, c and d) 5 mA_{rms}.
Input sensitivity	:	10–1000 mV for F.S.O.
Input impedance	:	<100 Kohm.
Sensitivity adjust – GAIN	:	max. ±50% of signal output.
R-balance adjust – ZERO	:	max. ±25% of F.S.O.
Output signal	:	a) 4–20 mADC; RL < (Vp–10 V)/22 mA b) 0–20 mADC, RL < (Vp–10V)/22 mA c) 0–5 VDC, RL > 250 ohm d) +5/–3 VDC, RL > 2 Kohm.
Non-linearity	:	<0.1%.
Phase compensation	:	max. 45°.
Bandwidth (–3 dB)	:	DC – 160 Hz (dependent on carrier frequency).
Ripple	:	<0.05% of output signal at max. bandwidth.
Temperature range	:	0–70°C.
Temperature coefficient		
– of sensitivity	:	<0.02%/°C of output signal.
– of zeropoint	:	<0.02%/°C of F.S.O.
Screwterminal connection	:	11 – poles, max. 1.5 mm² wire.