SUB STANTIATING DESIGN PARAMETERS OF A MULTI FUNCTIONAL MILKING MACHINE

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Abstract

Nowadays, large-scale dairy units, where milking machines are completed with automatic controls for milking mode control, are built alongside with farms with tie-up housing of small groups of cows. In these farms it is expedient to use multi-functional milking machines that allow performing such major process operations as increasing the milk yield of newly-calved cows in the maternity barn and milking the core herd. The goal of this study is to make the machine-based milking of cows more efficient by developing a multi-functional milking machine with substantiated operation modes. The research objectives are to determine the area of upgrades and develop the design and process layout of a multi-functional milking machine; identify the operating parameters of the milking machine’s upgraded vibration pulser; identify
the physiological parameters of the milking machine’s effect on the mammary gland in various milking modes and substantiate the operating parameters of the multi-functional milking machine. To stimulate a full milk flow reflex at the beginning and the end of the milking process, the developed design and process layout allows massaging the udder by microscale vibrations of the teat rubber of 1 to 2 mm in amplitude and affecting the udder nipples with a low vacuum pressure of 33 to 38 kPa, taking account of the animals’ physiological features. To identify the operating parameters of the milking machine and determine the physiological parameters of its effect on the mammary gland, laboratory plants with a Pulso Test Comfort vacuum and pulsingmeter and an Artificial-Udder test bench were used. Characteristic curves were derived to show the vacuum pressure-time relation in the interstitial and subteat areas of the teat cups; in addition, these relations were summated to derive the characteristic curve of differential pressure in the chambers. The physiological parameters of the milking excitants’ effect on the mammary glands were calculated.

The operating modes of the test machine (single-phase low-vacuum mode with continuous stimulation and three-phase mode with controlled stimulation) and their parameters were set.

Key words: Subteat and interstitial chambers, milking mode, stimulating, capacity, milking machine, massage

I. Introduction

Nowadays, large-scale dairy units, where milking machines are completed with automatic controls for milking mode control, are constructed alongside with farms with tie-up housing of small groups of cows. In these farms it is expedient to use multi-functional milking machines that allow performing such major process operations as increasing the milk yield of newly-calved cows in the maternity barn and milking the core herd. However, according to the analysis of available portable milking machines, the industry has not developed by now the manufacture of multi-functional milking equipment with a full range of milking mode variables for bucket milking. From this perspective, the scientific relevance of this paper is in the need for developing the milking machine design for increasing the adaptability and robustness of portable bucket milking of small groups cows with tie-up housing.

II. Materials and Methods

To determine the operating parameters of the multi-functional stimulating milking machine (MFSMM), the test measurements of cyclic vibrations in the teat cup chambers were conducted at a vacuum gage pressure of 48 and 38 kPa, with the disconnected and connected stimulating assembly of the upgraded vibration pulser, respectively. That said, all the teat cups of the developed machine were closed with attached plugs and the subteat and interstitial cup chambers were connected to a Pulso Test Comfort pulsation and vacuum meter.

The cyclic pressure fluctuations in the teat cup chambers, caused by the vibration pulser with a disconnect table high-frequency assembly, were measured and analyzed on a special-purpose laboratory facility. This facility consists of teat cups with plugs, a header with a simultaneous fluctuation distributor, a vibration pulser with a
disconnect able high-frequency assembly, a milk receiver, a vacuum duct section with an Inter Puls Stabilvak vacuum adjuster, a vacuum gage, and a vacuum lock, a Pulso Test Comfort oscillation and vacuum meter, and connection hoses.

According to ISO 5707, a pulsation cycle consists of four phases, i.e., pumping out (A), vacuum (B), blow off (C), and pressurization (D).

Pulso Test Comfort measures cyclic vacuum fluctuations in the teat cup chamber every 2 ms and with an outbound parameter increment of 0.1 k Pa. That said, the measurement error does not exceed 0.6 k Pa. The plots of vacuum pressure fluctuations are displayed on the LCD screen. In addition the PULSATION program processes the information received from embedded pressure sensors and transfers to the computer the following data in Microsoft Excel tables: maximum and minimum vacuum gage pressure in the teat cup chambers, k Pa; vacuum pulse repetition frequency, min⁻¹; suction/compression phase ratio; phase length, ms; operation cycle length, ms. Then the recorded information was analyzed and the operating parameters of the milking machine were determined.

The machine capacity and the physiological parameters of the milking excitants’ effect on the mammary gland were determined in the test studies of cyclic vibrations in the teat cup chambers while obtaining a pseudo-milk liquid on the Artificial Udder bench. The test studies included the experimental measurements of the capacity of the developed milking machine at a vacuum gage pressure of 32, 34, 36, and 38 k Pa, with the vibration pulser used in stimulating mode when atmospheric pressure was supplied to the supplementary control sleeve; the measurements were also made in main milking mode at a vacuum gage pressure of 48 k Pa, with the pulser used in pulsation mode by blocking the high-frequency vibration pulser assembly with the vacuum pressure supply to that pulser through a supplementary control sleeve. In addition, the capacity of the Nurlat three-phase reference machine was determined at a vacuum pressure of 33, 36, 38, and 48 k Pa.

The liquid from the artificial udder was withdrawn using the gradually developed milking machine through head pieces of 2 mm in diameter mounted on the pseudo-teats of the artificial udder. The withdrawn liquid volume was recorded using a milk meter for individual milk control during milking.

The developed milking machine was tested as follows: an NVU-60-2 water-circuit facility was put into operation, a necessary vacuum pressure value was set using the vacuum meter, the machine was put into operation, and a stopwatch was used for timing. Each test lasted at least 4 to 5 minutes and was repeated three times.

Then the milking machine capacity was found as

\[ Q = \frac{V}{t}, \]

Where \( Q \) is the capacity, l/min; \( V \) is the withdrawn liquid volume, l; \( t \) is the test duration, min.
The physiological parameters of the milking excitants’ effect on the mammary gland of the MFSMM and the Nurlat reference machine were determined using the Pulso Test Comfort pulsation and vacuum meter.

The plots of pressure changes in the teat cup chambers were read when withdrawing the pseudo-milk liquid at 4.8 and 5.5 l/min through the 2 mm head pieces of the pseudo-teats at a vacuum gage pressure of 48 and 38 kPa, respectively, with the disconnected and connected stimulating assembly of the vibration pulser of the developed machine.

The program made up in Microsoft Excel using the derived curves of the vacuum gage pressure-time relation in the subteat space of the teat cups summates the indicated plots and draws the characteristic curve of the differential pressure in the chambers and the characteristic curve of the teat rubber closure vacuum.

The physiological parameters of the milking excitants’ effect on the mammary gland were calculated using the oscillograph plots of milking.

The maximum pressure \( P_{\text{max}} \) (k Pa) of the teat rubber on the teat tissue is found as

\[
P_{\text{max}} = P_{\text{n. max}} - P_{\text{cl}}
\]

where \( P_{\text{n. max}} \) is the maximum differential pressure in the subteat and interstitial area of the teat cups per compression stroke, k Pa;

\( P_{\text{cl}} \) is the value of the teat rubber closure vacuum, k Pa.

The vacuum load \( F_m \) (N∙s) on the udder tissue per minute is found as

\[
F_m = P_{\text{p. avg}} \cdot t_{\text{cl}} \cdot S \cdot n \cdot 60
\]

Where \( P_{\text{p. avg}} \) is the average vacuum gage pressure in the subteat chamber, kPa; \( t_{\text{cl}} \) is the operation cycle length, s; \( n \) is the pulser vibration frequency, Hz; \( S \) is the cross-section area of the teat rubber, m\(^2\); \( S = \pi \cdot d^2 / 4 \), where \( d \) is the internal diameter of the teat rubber, m.

The vacuum load per milking period \( F_{\text{mlk}} \) (N∙s) is found as

\[
F_{\text{mlk}} = F_m \cdot t_{\text{mlk}}
\]

where \( t_{\text{mlk}} \) is the milking period length, min. The value used in the calculations was \( t_{\text{mlk}} = 6 \) min.

The maximum stretching force \( F_{\text{p. max}} \) (H) affecting the teat from the vacuum gage pressure is found as

\[
F_{\text{p. max}} = h_{\text{max}} \cdot S
\]

Where \( h_{\text{max}} \) is the maximum vacuum gage pressure in the subteat chamber, k Pa.

Thus the calculated indexes specified above allow evaluating the design and operating parameters of the developed milking machine for compliance with the physiological characteristics of the milking cow by comparing the design parameters of the ef-
fect on the mammary gland (pressure on the teat, vacuum load, and maximum stretching force) with the norms from ISO 5707-87.

III. Results

The design and process layout of the milking machine (Fig. 1) has been developed. At the beginning and end of the milking process this layout allows massaging the udder for stimulating a full milk yield reflex by producing microscale vibrations of the teat rubber of 1 to 2 mm in amplitude and, at the same time, affecting the udder teats at a low vacuum pressure of 33 to 38 k Pa in proportion to the animal’s physiology.

To implement the massage simulation function, it is proposed to equip the milking machine with an upgraded vibration pulser with a disconnectable stimulating assembly. This pulser is based on the well-known pulser ADU.02.200 and differs from the predecessor by having three sleeves, namely a constant vacuum gage pressure sleeve, an alternating vacuum gage pressure sleeve, and a supplementary control sleeve. The latter connects the pulser either to vacuum or to atmospheric pressure and, therefore, allows feeding variable pressure vacuum and pulses to the interstitial chambers of the teat cups during the suction stroke, which makes the walls of the teat rubber vibrate with an amplitude of 1 to 2 mm and frequency of 10 Hz. The disconnection and connection gear of the stimulating assembly is mounted in the milking bucket lid and responsible for switching between operating modes when a certain milk yield value is not reached or exceeded. The above indicated gear of control by supplying atmospheric or vacuum gage pressure to the vacuum level control assembly also allows changing the vacuum level from high to low and the other way round.

The milking machine works as follows. At the beginning of the milking process milk trap 9 takes the upper position, which is ensured by the weight of load element 12.  

1 is the teat cups; 2 is the header; 3 is the pulser; 4 is the milk tank; 5 is the milking mode control assembly; 6 is the vacuum level control assembly; 7 is the distributor; 8 is the receiver; 9 is the milk trap; 10 is the control chamber; 11 is the control shaft; 12 is the load element; 13 is the stimulating assembly of the vibration pulser; 14 is the pulsing assembly of the vibration pulser; 15 and 16 are the variable pressure chambers; 17 is the throttle valve; 18 is the permanent vacuum sleeve; 19 is the valve; 20 and 21 are the membranes; 22 is the control valve.
Fig. 1: Design and process layout of the multi-functional stimulating milking machine

That said, atmospheric pressure spreads through the duct of control shaft 11 and distributor 7 to variable pressure chamber 1 of vacuum level control assembly 6. Valve 17 allows setting a permanent vacuum pressure of 33 to 38 kPa in cavity G by throttling orifice ZH connecting cavities E and G. The same vacuum level is set through sleeve 18 in pulser 3, milk tank 4, and header 2. At the same time, atmospheric pressure spreads through the duct of control shaft 11 and distributor 7 to variable pressure chamber 15 of high-frequency assembly 13 of vibration pulser 3.

Atmospheric pressure is also supplied to variable pressure chamber 16 of assembly 14. This will ensure the joint and sequential operation of assemblies 14 and 13 of pulser 3, which allows getting milk at a low vacuum pressure of 33 to 38 kPa, with microscale vibrations of teat tubes. This will make the milking out process more complete by supporting the milk yield reflex and allow producing a more adequate effect on the mammary gland as long as the milk yield does not reach its peak. As the milk withdrawal intensifies, the milk from teat cups 1 goes through header 2 to milk trap 9 until the latter is full. The milk-filled trap will be heavier than the load element, and, therefore, the latter will take the extreme bottom position. Vacuum gage pressure spreads through the duct of control shaft 11 and distributor 7 to chamber 1 of assembly 6. Valve 19 overcomes the resistance of the spring by the action of vacuum force on membrane 20 and takes the extreme bottom position to close orifice B that connects the atmosphere to the internal cavities of assembly 6. That said, the vacuum gage pressure in cavity G is equalized with the pressure in cavity E to reach 50 kPa. The same vacuum pressure is set through sleeve 18 of assembly 14 in pulser 3, milk...
tank 4, and header 2. At the same time, vacuum gage pressure spreads through the control shaft duct and distributor 7 to the variable pressure chamber of assembly 13 of pulser 3. Assembly 13 will stop running, which will allow the milking machine to work in a standard two-stroke mode with the maximum capacity at a vacuum pressure of 50 kPa.

As the milk withdrawal becomes less intensive in the final part of the milking process due to the weight of load element 12, milk trap 9 takes the upper position. That said, atmospheric pressure spreads through the duct of control shaft 11 and distributor 7 to variable pressure chamber 1 of assembly 6. Valve 17 allows setting a permanent vacuum pressure of 33 to 38 kPa in cavity G by throttling orifice ZH connecting cavities E and G. The same vacuum pressure level is set through sleeve 18 in pulser 3, milk tank 4, and header 2. At the same time, atmospheric pressure spreads through the duct of control shaft 11 and distributor 7 to variable pressure chamber 15 of high-frequency assembly 13 of pulser 3. Atmospheric pressure is also supplied to variable pressure chamber 16 of assembly 14. This will ensure the joint and sequential operation of assemblies 14 and 13 of pulser 3, which makes possible machine-based aftermilking at a low vacuum pressure of 33 to 38 kPa, with microscale vibrations of teat tubes. This will make the after milking process more complete by supporting the milk yield reflex and prevent the teat-cup crawl owing to the semi-compressed teat tubes.

In addition, the design of the multi-functional milking machine allows it to work in other modes and as a low-vacuum stimulating milking machine with the milk trap fixed in the upper position, which ensures a sparing milking mode with a simultaneous stimulating effect.

For the theoretical substantiation of the design and operation parameters of the milking mode control assembly see.

For the plots of the cyclic vibrations in the interstitial and subteat chambers of the teat cups of the tested machine in main mode with the disconnected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 48 kPa and in stimulating mode with the connected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 38 kPa see Fig. 2.
Fig. 2: Plots of the cyclic oscillations in the interstitial and subteat chambers of the teat cups of the tested machine with a disconnected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 48 kPa (a) and with a connected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 38 kPa (b)

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The maximum and minimum vacuum pressures in the interstitial and subteat chambers of the teat cups, pulse repetition frequency, phase lengths and ratios, and operation cycle lengths in main and stimulating milking modes are presented in Tables 1 and 2.

Table 1: Operating parameters of the developed milking machine in main milking mode

| Vacuum P [kPa] | Pulse repetition frequency, Hz (min⁻¹) | Phase ratio (%) | Phase fraction [%] | Operation cycle length (ms) |
|----------------|--------------------------------------|----------------|--------------------|-----------------------------|
| chambers       | suction                              | compression    | A      | B      | C      | D      | A      | B      | C      | D      | Total |
| Interst.       | 48.1                                 | 0.84 (50.3)    | 75     | 25     | 14.6   | 60.6   | 14.7   | 9      | 1      | 7      | 3      | 6     | 1     | 7     | 9     | 1     | 121.5 |
| Sub-teat       | 48.2                                 |                |        |        |        |        |        |        |        |        |        |       |       |       |       |       |

Table 2: Operating parameters of the developed milking machine in stimulating milking mode

| Vacuum P [kPa] | Pulse repetition frequency, Hz (min⁻¹) | Phase ratio (%) | Phase fraction [%] | Operation cycle length (ms) |
|----------------|--------------------------------------|----------------|--------------------|-----------------------------|
| chambers       | suction                              | compression    | A      | B      | C      | D      | A      | B      | C      | D      | Total |
| Interst.       | 29.9                                 | 1.15 (70.3)    | 70     | 30     | 14.4   | 55.7   | 10.9   | 19.1   | 1      | 1      | 4      | 61    | 9     | 1     | 6     | 2     | 9     | 5     | 8     | 82    |
| Sub-teat       | 38.4                                 |                |        |        |        |        |        |        |        |        |        |       |       |       |       |       |

For the plots of pressure fluctuations in the chambers of the teat cups of the tested machine in sparing milking mode with the connected high-frequency vibration pulser assembly at a vacuum gage pressure of 38 kPa and in main milking mode with the disconnected high-frequency vibration pulser at a vacuum gage pressure of 48 kPa, with the pseudo-milk liquid withdrawn at a rate of 4.8 and 5.5 l/min and with the 2 mm head pieces of the pseudo-teats and see Fig. 3.
a) Plot of pressure changes in interstitial chambers of teat cups

b) Plot of pressure changes in subteat chambers of teat cups
   Plot of differential pressure between subteat and interstitial chambers of teat cups

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Note. The left and the right Y-axes correspond to the plot of pressure changes in interstitial chambers of teat cups and to the other plots, respectively.

Fig. 3: Plot of pressure changes in the teat cup chambers in main (a) and stimulating (b) milking mode.

For the results of determining by test the capacity of the multi-functional stimulation milking machine in stimulating mode with the connected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 32, 34, 36, and 38 kPa and in main mode with the disconnected high-frequency assembly of the vibration pulser at a vacuum gage pressure of 48 kPa see Table 3. For the comparative capacity relations of the developed and the reference machine see Fig. 4.

Table 3: Results of determining the capacity $Q$ (l/min) of the milking machine by test

| Index | Vacuum gage pressure value in operation mode, kPa |
|-------|--------------------------------------------------|
|       | Main       | Stimulating |
|       | 48 | 32 | 34 | 36 | 38 |
| Test 1 | 5.52 | 3.62 | 4.02 | 4.42 | 4.83 |
| Test 2 | 5.48 | 3.58 | 3.99 | 4.39 | 4.81 |
| Test 3 | 5.49 | 3.61 | 3.98 | 4.38 | 4.79 |
| Average | 5.50 | 3.60 | 4.00 | 4.40 | 4.81 |

Fig. 4: Capacity of the tested and the reference milking machine.

For the physiological parameters of the milking excitants’ effect on the mammary gland of the developed and the reference (Nurlat) milking machine see Tables 4 and 5.
Table 4: Parameters of the effect on the mammary gland of the developed and the reference milking machine in low-vacuum stimulating milking mode

| Indexes                  | $P_{max}$, kPa | $F_m$, N$\cdot$s | $F_{p,max}$, N |
|--------------------------|----------------|------------------|----------------|
| Test machine             | 10.8           | 582.5            | 13.1           |
| Nurlat                   | 22.5           | 534.1            | 11.2           |
| Normacc. to ISO 5707-87  | –              | 700...1200       | ≤17            |

Table 5: Parameters of the effect on the mammary gland of the developed and the reference milking machine in main milking mode

| Indexes                  | $P_{max}$, kPa | $F_m$, N$\cdot$s | $F_{mlk}$, N$\cdot$s | $F_{p,max}$, H |
|--------------------------|----------------|------------------|----------------------|----------------|
| Test machine             | 14.0           | 765.8            | 4594.8               | 17.0           |
| Nurlat                   | 27.1           | 747.2            | 4483.2               | 16.8           |
| Normacc. to ISO 5707-87  | –              | 700...1200       | 3600...6000          | ≤17            |

IV. Discussion

According to the analysis of Tables 1 and 2, the changes in the vacuum gage pressure and the (dis-) connection of the stimulation assembly of the upgraded vibration pulsers change the pulse repetition frequency, strokes ratio, and, therefore, operation cycle length. For instance, at a vacuum gage pressure $P=48$ kPa and with the stimulation assembly disconnected, the pulse repetition frequency $n$ is 0.84 Hz ($50.3$ min$^{-1}$), the suction/compression phase ratio is 75 to 25 %, and the operation cycle length $t_{cl}$ is 1.215 s. At $P=38$ kPa and with the stimulation assembly connected, $n$ is 0.84 Hz ($50.3$ min$^{-1}$), the suction/compression phase ratio is 70 to 20 %, and $t_{cl}$ is 0.829 s.

With the switchover to the compression stroke in the developed machine (Fig. 2), the differential pressure between the interstitial and the subteat chambers of the teat cups starts to intensively increase; that said, at zero liquid withdrawal intensity the subteat vacuum pressure remains almost unchanged.

It follows from Fig. 3 that the variable pressure pulses (vacuum atmosphere) supplied to the interstitial chambers of the teat cups during the suction stroke allow massaging the udder teats by producing microscale vibrations of the teat rubber walls.

According to the analysis of Fig. 4, the machine capacity increases with both, rising and dropping vacuum gage pressure. In addition, at the equal level of vacuum gage pressure the Nurlat pairwise milking machine shows a weaker suction ability than the tested machine, although the teat rubber in the latter is half-compressed. At a vacuum gage pressure of 32 kPa Nurlat and the tested machine have a suction rate of 3.5 and 3.6 l/min and at 38 kPa this rate is 4.2 and 4.8 l/min, respectively. The higher capacity of the developed milking machine compared with Nurlat results from the longer suction stroke (70 vs. 60 %) and higher pulsing frequency (70.3 vs. 44.4 min$^{-1}$) and also from the drop in the average differential pressure to 1.57 kPa between the interstitial and the subteat chambers during the suction stroke when the liquid is withdrawn.
Since the tested milking machine is intended for use not only in three-phase mode with controlled stimulating but also for the permanent stimulation of milk yield to obtain more milk from newly-calved cows, it is proposed to increase the low-vacuum pressure from 33 to 38 kPa to maintain the sufficient capacity of the machine.

According to the analysis of Tables 4 and 5, the characteristics of the effect on the mammary glands of the tested and the reference machine in stimulating and main milking mode do not exceed the norms set by ISO 5707-87. However, the teat massage by the developed machine is more adjusted to physiology than Nurlat (the pressure on the teat in low-vacuum and main mode is 10.8 vs. 22.5 kPa and 14 vs. 27.1 kPa, respectively) and allows withdrawing the pseudo-milk liquid more efficiently.

V. Conclusion

The facility most suitable for the bucket milking of small groups of cows with tie-up housing is the multi-functional stimulation milking machine that completely and safely withdraws milk from the udder during various process operations such as milking the core herd, milking out newly-calved cows in the maternity barn, etc. The milking machine the design and process layout of which is developed consists of two-chamber teat cups, a header, a vibration pulser with a disconnectable high-frequency assembly, a milking mode control assembly, a vacuum level control assembly with a magnetic valve switch, and a receiver with the subteat chamber choke membrane.

The operating modes set for the tested machine are single-phase low-vacuum mode with permanent stimulation and three-phase mode with controlled stimulation. The vacuum gage pressure generated by the machine in the stimulation, main milking, and aftermilking phase is $38^{\pm2}$, $48^{\pm2}$, and $38^{\pm2}$ kPa, respectively.

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