Study of Milking Machine with Independent Vacuum Mode

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Abstract — *This article describes the program and experimental procedure of studies as well as comparisons of a serial milking machine and milking machine with independent vacuum mode; oscillograms and curves of their operations are presented. The experimental studies have been based on the developed partial and appropriate standard procedures as well as State Standards GOST. Optimization of milk ejection from cow udder is proposed using experimental milking machine with independent vacuum based on similarity theory and dimensional analysis in combination with experimental design. Fat content in milk was measured by the Gerber method (sulfuric acid) according to State Standard GOST 5867-95. Milk samples for analysis were taken at start and end of preliminary and final periods as well as each five days of the main period. Mass fraction of proteins in milk was determined by formal titration, and casein content in milk was determined by the Mattiopulo method. Milk density, content of milk solids and content of nonfat milk solids were determined by predictions. Advantages of the milking machine with independent vacuum mode have been highlighted, final results of the performed work have been summarized. The main design and engineering parameters of the experimental milking machine with independent vacuum are as follows: rated vacuum pressure in vacuum line: 48±1 kPa; in teat cup: 30-33 kPa; ejected milk weight per one operation cycle of actuator: 3.0 g/s….7.0 g/s. Average intensity of milk ejection in experimental group in comparison with reference group increased in average by 9.1%, and fat content in milk increased in average by 0.11%. The experimental milking machine exerts more sparing effect on cow teats, herewith, vacuum load during milking has decreased by 30%, and total milking time has been reduced from 0.7 to 1 min in comparison with ADU-1 serial milking machine.*

Keywords — *milking machine with independent vacuum mode, milk ejection, milking efficiency, oscillograms, milk ejection intensity, vacuum load on cow teat.*

I. INTRODUCTION

This work is aimed at improvement of efficiency of cow machine milking by development of milking machine with independent vacuum on the basis of reasonable parameters and operation modes.

Analysis of methods and tools of machine milking described in the works by Averkaev A. A., Admin Ye. N, Andrianov Ye. A, Bunin I. A., Valdman E. A., Vasin B. I., Gorodetskaya T. K., Karanaev Yu. S., Kartashov L. P., Kelpis E. A., Kirsanov V. V., Kokorina E. P., Korolev V. F., Krasnov I. N., Kuzmin A. Ye., Kurochkin A. A., Melnikov S. V., Ogorodnikov P. I., Petukhov N. A., Pronichev N. P., Solovev S. A., Skorkina S. A., Uzhik V.F., Uzhik O.V., Ulyanov V. M., Utolin V. V., Khripin V. A., Tsoi Yu. A., Chekhunov O. V., Shakhov V. A., and others demonstrated that the issue of safe milk ejection should be studied in more details.

The main theoretical aspect of the work is dynamic analysis of milk transportation from collector to milk delivery line.

During squeeze phase atmospheric pressure is applied from pulsator to the membrane inlet, and the membrane lifts upward displacing milk to milk delivery line via hose.

The Bernoulli equation for cross section on free milk surface in the collector (1-1) and in the milk delivery line (2-2) will be as follows:

$$Z_1+p_1/\gamma+\alpha_1 V_1^2/2g=Z_2+p_2/\gamma+\alpha_2 V_2^2/2g+h\omega,$$

where Z_1, Z_2 are the height of position of the collector and the milk delivery line, respectively, m; P_1, P_2 are the hydraulic pressure in the collector and in the milk delivery line, respectively, kPa; $\alpha_1 \approx \alpha_2 \approx 1$; V_1, V_2 are the milk velocity at the collector outlet and at the milk delivery line inlet, respectively, m/s; h is the sum of all losses along the hose length and local resistances, m.

$$h\omega = \xi_{rev.valve.} V^2/2g+ \xi_{exit\ branch} V^2/2g+\lambda_{lhose} V^2/d_{hose} 2g+ \xi_{milk\ in.} V^2/2g\ ,$$

where $\xi_{rev.valve.}$; $\xi_{exit\ branch}$; $\xi_{milk\ in.}$ are the local resistances of reverse valve, exit branch of collector, and inlet to milk delivery line, respectively.

Taking this into account, the required pump head is determined as follows:

$$H_{pump.} = Z_2 - Z_1 + h\omega$$

Therefore:

$$H_{pump.}= Z_2 - Z_1 + V^2/2g\ (\xi_{rev.valve.} + \xi_{exit\ branch} + \frac{\lambda l_{hose}}{d_{hose}} + \xi_{milk\ in.}).$$

Maximum pressure drop between the collector and the milk delivery line will take place during head motion of milk, when all hose from the collector to the milk delivery line is filled with milk, the main pressure drop is determined by the difference: $(Z_2 - Z_1 \approx 1.5 \div 1.7\ m)$. Herewith, the vacuum in the collector also decreases by the maximum value.

While controlling the stroke ratio, it is possible to avoid milk and air plugs in the milk hose and to decrease the coefficient of hose filling with milk; herewith, the air volume displaced by the membrane should be higher than the liquid volume conveyed per one cycle.

Total cycle duration of milk pumping out should be executed per squeeze stroke:

$$\begin{cases} t_{ui} = t_{squeeze} \\ t_{ui} = t_{mi} + t_{in.i} \end{cases}$$

where t_{ui} is the duration of milk and air delivery, s; t_{mi} is the duration of milk pumping out, s; $t_{in.i}$ is the duration of fresh air inlet into the milk hose.

On the basis of the ratio $t_{mi} / t_{in.i} = K_B$, we have:

$$t_{ui} = t_{mi} + t_{mi}/K_B = t_{mi}(1+1/K_B).$$

Delivery of membrane pump Q can be determined as follows:

$$Q = 60\ \eta_0 Vn,$$

where η_0 is the pump efficiency, V is the volume of pump chamber, n is the number of pump double strokes.

Volume of the pump chamber $(F_m S_m)$ is determined by vacuum in collector P_c = 36-40 kPa:

$$V = E\ V_c = E(4V_{ms} + V_{mc})$$

With consideration for the aforementioned, the pump delivery Q can be written as:

$$Q = 60\ \eta_0 E\ (4V_{ms} + V_{mc})n$$

the number of double strokes is $n = 60/(t_s+t_{squeeze})$

Finally, the delivery is determined as follows:

$$Q = 60\ \eta_0 E\ (4V_{ms} + V_{mc})\ (60/(t_s+t_{squeeze}))$$

II. PROGRAM AND PROCEDURE OF COMMERCIAL TESTS

The aim of the test is determination of operability and efficiency of the experimental milking machine with independent vacuum [1]. ADU-1 milking machine was selected as the reference for comparison. The testing program stipulated for comparative tests with determination of the following properties:

1. Total milking time, s;
2. Duration of machine milking, s;
3. Maximum intensity of milk ejection, kg/min;
4. Average intensity of milk ejection, kg/min;
5. Duration of machine after-milking, s;
6. Milk yield per minutes, kg;
7. Residual milk portion, ml;
8. Milk yield during morning and evening milking, kg;
9. Recording of machine milking oscillograms in various modes.
10. Analysis using dimastin reagent.
11. Milk quality indicators:

11.1. Milk density, kg/m^3;

11.2. Protein, wt %;

11.3. Casein, wt %;

11.4. Milk solids, %;

11.5. Nonfat milk solids, %;

11.6. Milk fat content, %.

Two groups of similar cows were arranged: experimental and reference. Milking was performed two times.

The tests were performed according to the procedure described in Table 1.

Milk density, milk solids, and nonfat milk solids were determined by predictions [2-4].

Table 1. Experimental Procedure

Group of tested cows	Number in group	Periods			Housing and milking conditions
		Preliminary (5 days)	Main (15 days)	Final (5 days)	
Experimental	3	ADM-200 serial milking parlor with experimental milking machine with independent vacuum			Tie-up Bucket milking
Reference	3	ADM-200 serial milking parlor, standard set			

Preparation of udder for milking, preparation of working place of milking operator, installation of milking cups on udder teats, and other procedures of machine milking were carried out according to the rules of machine milking [2-6].

In order to determine milk ejection intensity, the milking was performed into milk delivery line. Bucket with electronic scales was installed at the end of milk delivery line. The time of milk ejection per minutes was measured using an Agat mechanical stopwatch.

ADM-200 serial milking parlor with three two-row cubicles was used, Fig. 1.

ADM-200 serial milking parlor equipped with milking machines with independent vacuum and milking into milk delivery line, was used for comparison, Fig. 2.

Oscillograms were recorded by PulsoTest instrument (Germany), Fig, 3.

Fig. 1. Milking of reference group using an ADM-200 serial milking parlor with a standard milking machine [1, 2]

Fig. 2. Milking of experimental group using an ADM-200 serial milking parlor with the milking machine with independent vacuum [1, 2]

Fig. 3. PulsoTest instrument (Germany) for recording of oscillograms of cow machine milking [1, 2]

III. RESULTS

Commercial tests of milking machines were performed from December, 2012 to July, 2013 at Sakharovo milk farm, Tver State Agricultural Academy. The live weight of the cows was 550 kg, 1-2 periods of lactation with annual milk yield of 4,425- 46,76 l per previous lactation. The main experimental results are summarized in Tables 2 and 3 [1, 2].

Table 2. Commercial Tests of Experimental and Serial Milking Machines

Cow #	Preliminary period			Main period		
	Duration of machine milking, s	Milk ejection intensity, g/s	Manual after-milking, ml	Duration of machine milking, s	Milk ejection intensity, g/s	Manual after-milking, ml
	Reference group					
2534	890	24.4	107	890	24.6	102
2592	766	27.8	105	800	28.0	103
2503	769	28.4	110	797	28.8	101
	Experimental group					
2536	776	26.4	128	776	27.4	108
2587	697	30.6	219	717	30.8	153
2547	712	30.6	115	722	31.0	103

It can be seen in Table 2 that for one and the same time of machine milking of the reference and experimental groups of cows, the average milk ejection per second increased by 9.1%.

It can be seen in Table 3 that while milking using the experimental machine with independent vacuum, the milk yield in group increased by 2.6 kg in comparison with the preliminary period or by 4%. In the reference group, during the same time the milk yield increased by 1.4 kg (2%), the difference between the groups was 1.2 kg [2].

Table 3. Experimental Results of Milking Machines for Experimental Periods

	Experimental periods						
	Preliminary			Main			
	Amount of milk, kg						
	Milking 1	Milking 2	Q	Milking 1	Milking 2	Q	Difference, kg
	Reference group						
2534	8.0	13.8	21.8	7.6	14.0	21.6	-0.2
2592	7.2	13.2	20.0	7.2	13.6	21.4	1.4
2503	7.8	14.0	21.8	7.2	14.2	22.0	0.2
Total			63.6			65.0	1.4
	Experimental group						
2536	8.0	13.8	21.8	8.2	14.2	11.2	0.6
2587	7.2	13.2	21.0	8.2	14	11.1	1.2
2547	7.8	14.0	21.8	8.2	14.4	11.3	0.8
Total			64.6			67.2	2.6

Before machine milking, the first milk threads were squeezed and tested using dimastin reagent. During preliminary period affected cows were not detected. During analysis of milk obtained from the cows of reference group in the main period, the cows with positive response to the dimastin reagent were revealed. Later this was confirmed by settlement for one cow. Subclinical mastitis was detected. No inflammatory processes of latent mastitis were detected in the experimental group.

On the basis of experimental results, the curve of milk ejection intensity was plotted (Fig. 4) for the experimental milking machine with independent vacuum and the serial machine. It can be seen that the milk ejection intensity for the experimental milking machine with independent vacuum is higher and the milking time is lower than those of the serial milking machine.

Table 4 summarizes analyses of composition and quality of cow milk. The milk in the experimental group during the main period contained more fat than during the preliminary period (by 5.1%). During the tests the content of milk fat in the reference group increased only by 2.4%. Thus, in the milk of the experimental group, the fat content was higher by 2.7% than in the milk of the reference group [2].

In the milk of the experimental group during the main period the mass fraction of protein increased by 3.6%. During the tests the total protein content in the milk of the reference group increased by 0.7%. The total protein content in the milk of the experimental group increased by 2.8%. It follows from Table 4 that the casein content in the experimental group during the main period increased by 6.0% in comparison with the preliminary period. In the reference group, the casein content during the tests decreased by 4.9% in comparison with the preliminary period.

The content of milk solids in the experimental group during the main period also increased in comparison with the preliminary period by 6.7%, in the reference group the content of milk solids increased by 2.3%.

The content of nonfat milk solids in the experimental group (Table 4) during the tests increased by 4.4%, in the reference group, this property decreased by 1.3% at the start of the main period.

Therefore, the use of the experimental milking machine with independent vacuum allows not only to increase the milk yield efficiency but also to improve the milk composition [2, 5, 6].

Oscillograms of machine milking were determined upon various vacuum modes during the comparative tests of ADU-1 serial milking machine and experimental machine with independent vacuum (Figs. 5 and 6).

The oscillograms were processed and described, the obtained data for the vacuum modes were summarized in Table 5. It can be seen that the maximum specific pressure of teat cup liner on the teat tissue (P_{max}) decreased in average by 17.2 kPa, the minute vacuum load decreased at 40 kPa by 484.6 N·s, and at 50 kPa – by 474.8 N·s, which led to decrease in the vacuum load during total milking time. Maximum tension (F_{pmax}) acting on teat decreased by 4 N from the maximum value.

Therefore, it is possible to conclude that the use of the experimental milking machine with independent vacuum improves the performances of machine milking and, probably, promotes safe milk ejection from cow udders.

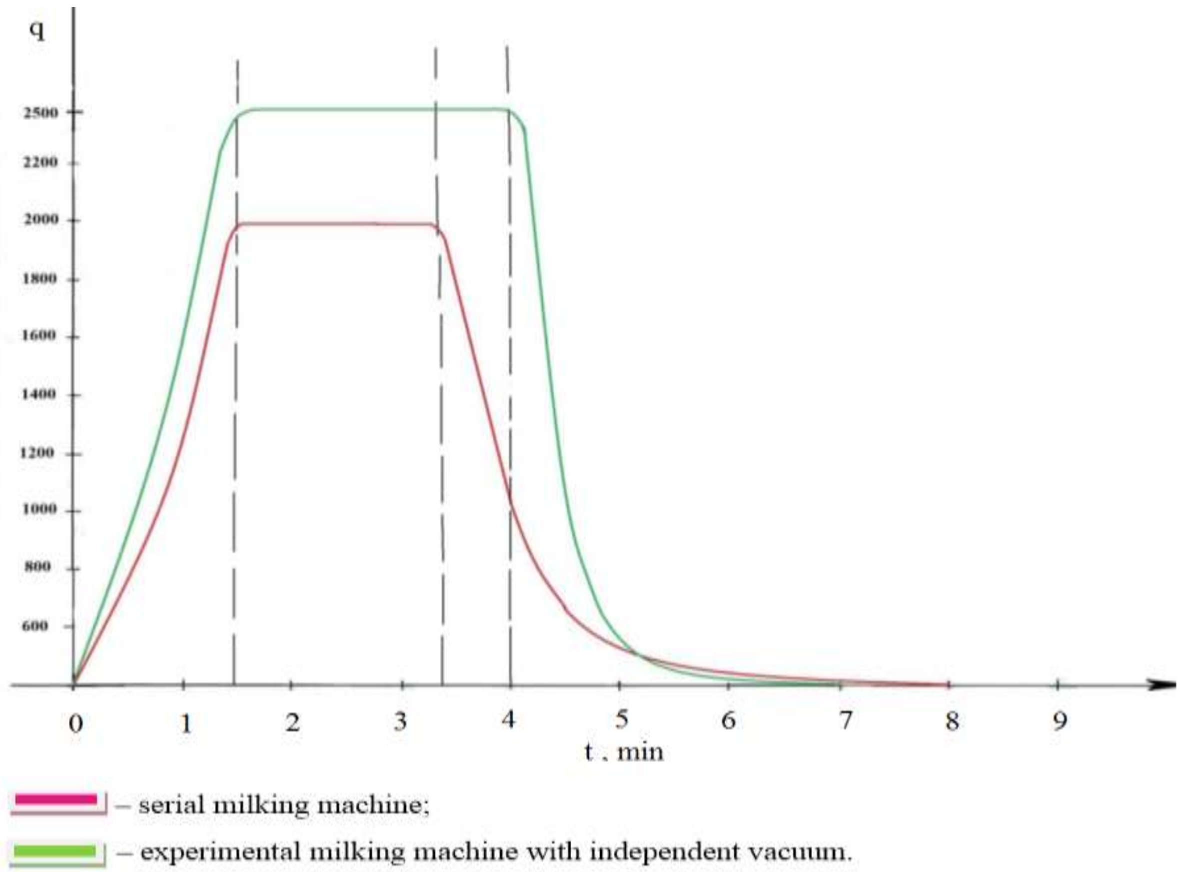


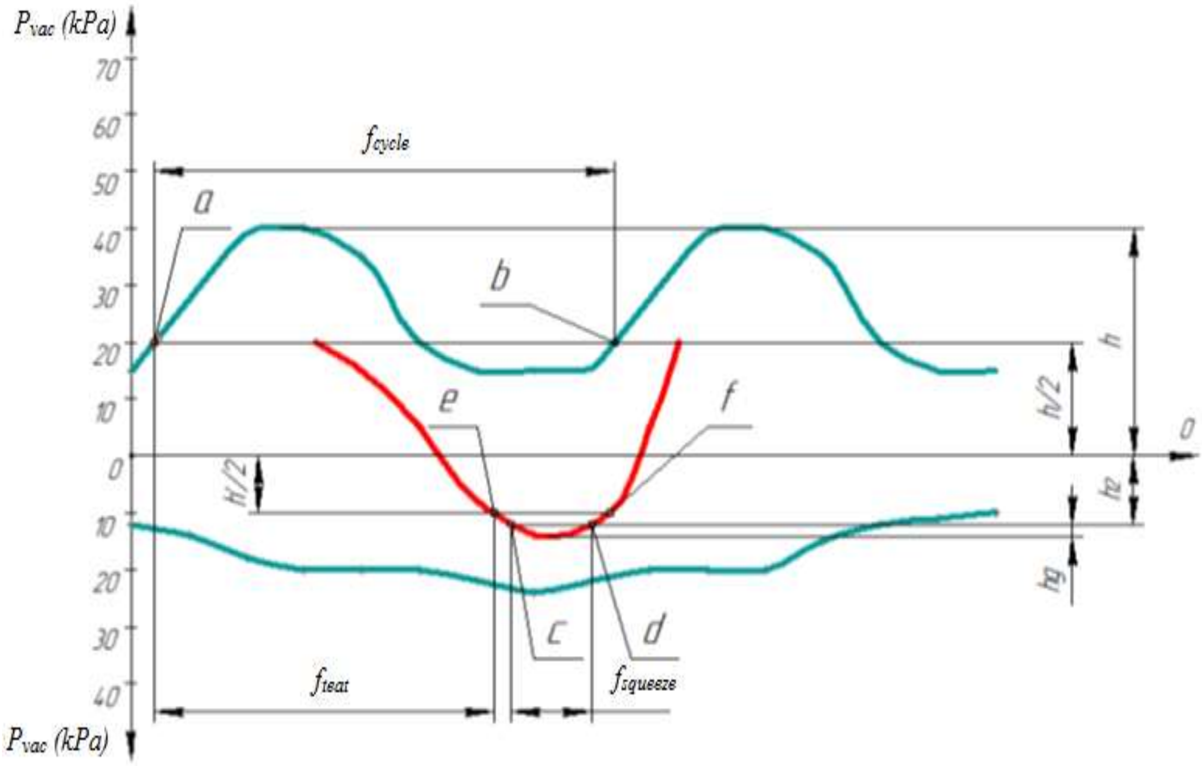
Fig. 4. Comparison of milk ejection intensity [2]

Table 4. Composition and Quality of Cow Milk

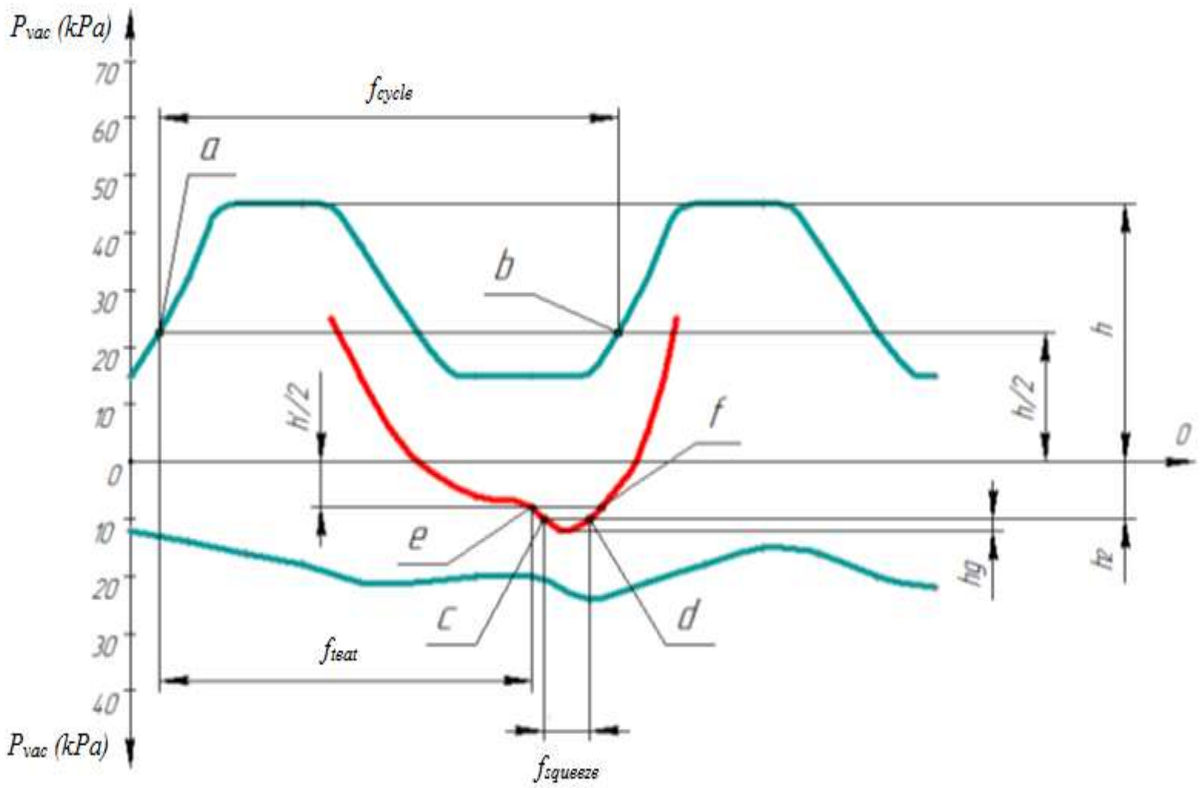
Cow #	Experimental periods													
	Preliminary							Main						
	Properties													
	Daily milk yield in terms of basic fat content, kg	Density, A	Fat, wt %	Protein, wt %	Casein, wt %	Milk solids,%	Nonfat milk solids,%	Daily milk yield in terms of basic fat content, kg	Density, A	Fat, wt %	Protein, wt %	Casein, wt %	Milk solids,%	Nonfat milk solids,%
Reference group														
2503	10.12	27.3	3.42	2.80	3.08	12.62	8.32	10.18	28.0	3.52	2.81	2.88	13.99	10.41
2592	9.34	27.6	3.82	3.15	2.90	12.08	8.58	10.43	27.8	3.93	3.22	2.20	10.89	10.73
2534	10.21	26.6	3.51	2.87	2.00	10.91	8.45	10.35	27.8	3.62	2.96	2.60	11.53	10.86
Total	29.67								30.96					
Average	9.89	27.2	3.58	2.93	2.66	11.87	8.46	10.32	27.86	3.69	2.95	2.56	12.14	8.35
±to preliminary period								+0.43	+0.66	+0.01	+0.02	-0.10	+0.27	-0.1
Experimental group														
2547	10.51	27.0	3.83	3.06	2.02	10.93	7.93	11.89	28.0	3.92	3.17	2.12	11.26	8.19
2536	11.25	28.0	3.79	3.03	2.90	11.51	8.23	11.56	29.2	3.83	3.10	2.84	12.48	8.66
2587	10.94	29.2	3.65	2.92	2.96	12.25	8.62	11.26	30.0	3.78	3.06	3.10	13.27	8.97
Total	32.7								34.71					
Average	10.91	28.1	3.75	3.0	2.63	11.56	8.26	11.57	29.06	3.84	3.11	2.69	12.34	8.61
±to preliminary period								+0.67	+0.96	+0.09	+0.11	+0.06	+0.78	+0.3

Table 5. Comparative Tests Of ADU-1 Serial Milking Machine and Experimental Milking Machine with Independent Vacuum

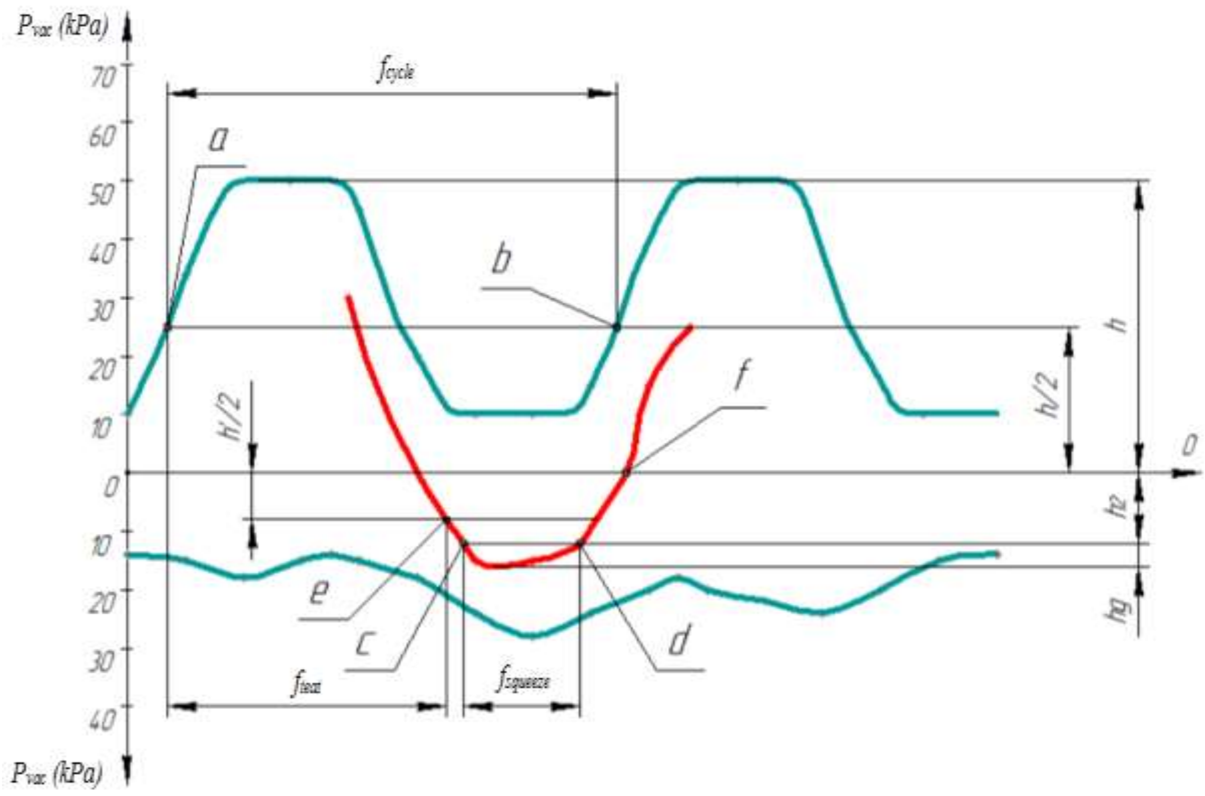
Properties	ADU-1 milking machine						Experimental milking machine					
	40 kPa		45 kPa		50 kPa		40 kPa		45 kPa		50 kPa	
Maximum specific pressure (P_{max}) of teat cup liner on teat tissue, kPa	4.10		3.86		4.89		3.57		3.66		4.26	
	4.34	4.26	4.34	3.70	4.94	4.93	3.77	3.65	3.13	3.22	4.30	4.29
	4.15		3.66		4.95		3.61		3.18		4.31	
Minute vacuum load (F_m) on udder teat, N*s	322.7		411.0		487.0		280.6		357.4		423.5	
	345.8	332.4	419.1	440.6	493.0	491.2	300.7	289.05	364.4	364.9	428.7	427.2
	328.6		559.0		493.9		285.8		372.7		429.5	
Vacuum load (F_{tmt}) per total milking time, N*s	1,620.2		2,057.8		2415.3		1,408.9		1,798.4		2,100.3	
	1,729.2	1,695.3	2,095.6	2,074.6	2,465.0	2,449.2	1,503.7	1,474.2	1,822.3	1,804.0	2,143.5	2129.7
	1,735.6		2,070.5		2,469.7		1,510.1		1,806.5		2,147.6	
Maximum tension ($F_{e\ max}$) acting on teat, N	1.9		3.54		3.25		1.66		2.36		2.84	
	2.1	2.09	2.98	2.94	3.08	3.20	1.88	1.83	2.60	2.57	2.68	2.78
	2.2		3.19		3.28		1.94		2.77		2.86	



a) Cow #2536; P_{vac} = 40 (kPa)

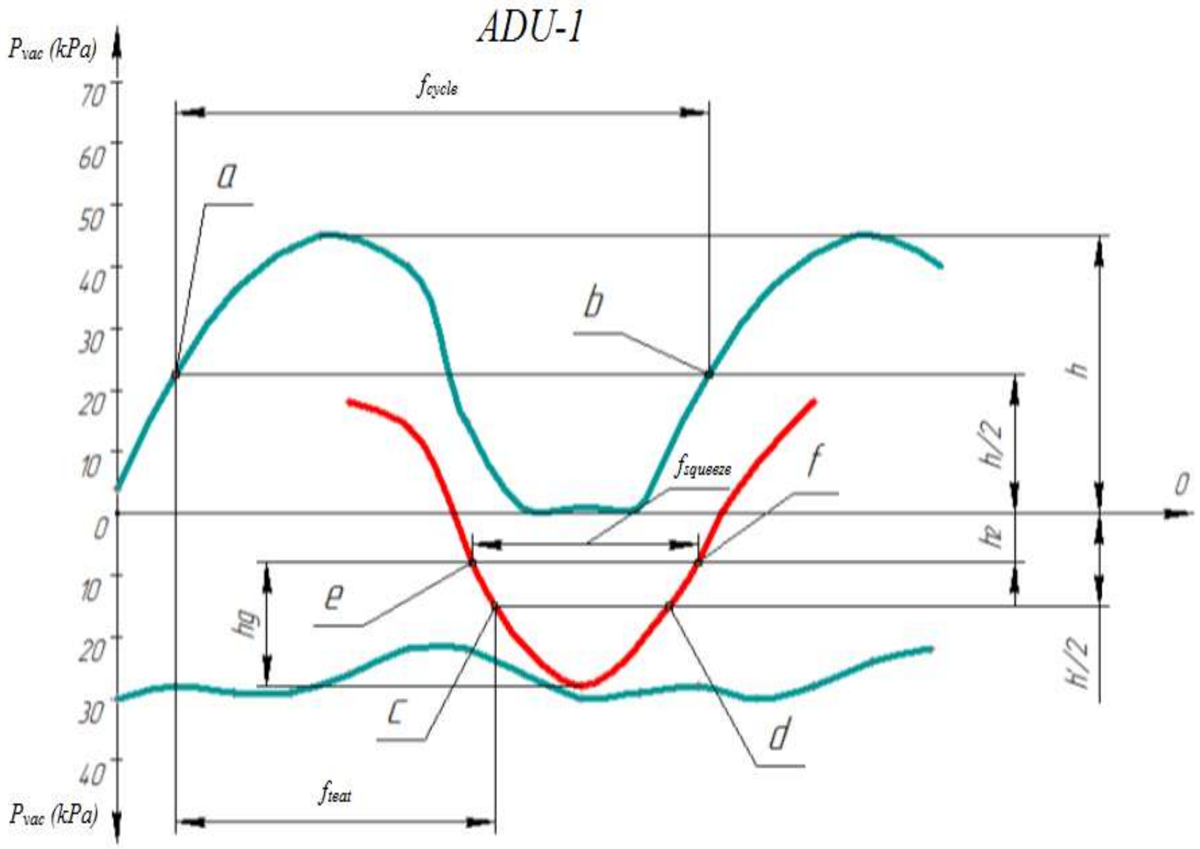


b) Cow #2503; P_{vac} = 45 (kPa)

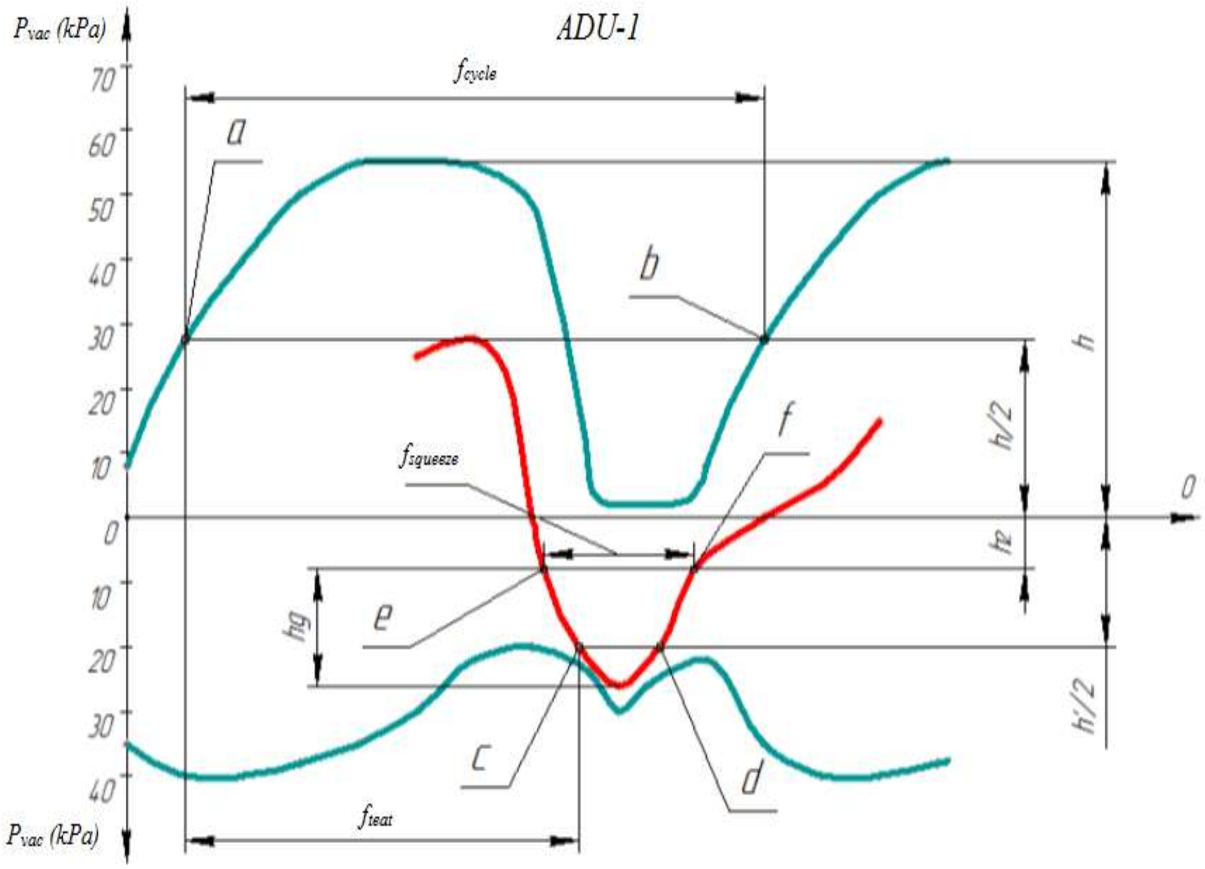


c) Cow #2536; P_{vac} = 50 (kPa)

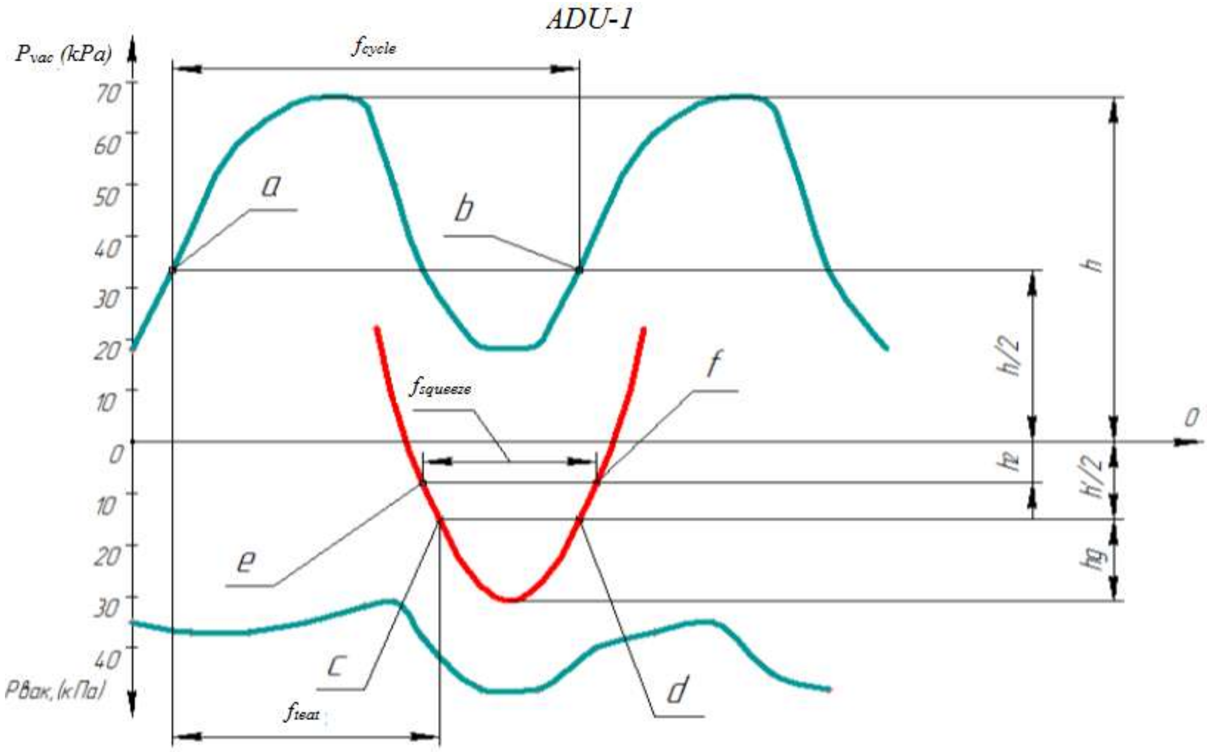
Fig. 5. Oscillograms of Milking Using the Experimental Milking Machine [1]



a) Cow #2503; P_{vac} = 40 (kPa)



b) Cow #2503; P_{vac} = 45 (kPa)



c) Cow #2503; P_{vac} = 50 (kPa)

Fig. 6. Oscillograms of Milking Using ADU-1 Milking Machine [1]

IV. CONCLUSIONS

1. Commercial tests of the experimental milking machine with independent vacuum demonstrated that the average intensity of milk ejection in experimental group in comparison with reference group increased in average by 9.1%, and fat content in milk increased in average by 0.11%.

2. On the basis of application of the similarity theory and dimensional analysis in combination with experimental design, the regression equations have been obtained confirming high convergence of theoretical and experimental studies (95%) and allowing to determine optimum design and engineering parameters of the experimental milking machine with independent vacuum: rated vacuum pressure in vacuum line: 48±1 kPa; in teat cup: 30-33 kPa; ejected milk weight per one operation cycle of actuator: 3.0 g/s….7.0 g/s.

3. It has been demonstrated that the experimental milking machine exerts more sparing effect on cow teats, herewith, vacuum load during milking has decreased by 30%, and total milking time has been reduced from 0.7 to 1 min in comparison with ADU-1 serial milking machine.

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