Vacuum Regulation with a VFD Controller: Preliminary Tests and Modeling of the Vacuum System

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Abstract. Using a variable frequency drive (VFD) in order to drive the vacuum pump of a milking machine allows a dramatic reduction in energy use, while still producing equivalent vacuum stability. The VFD technology is able to adjust the rate of air removal from the milking system by changing the speed of the vacuum pump motor. A PID controller was developed in order to command the electric motor driving the vacuum pump. The PID controller used by the vacuum regulating system was tuned using the Ziegler-Nichols tuning rules for the frequency response method. In order to proceed to a more systematic approach a mathematical model of the vacuum system was developed, assuming that the system consists of a single air tank, provided with a vacuum pump port and an air-using port. In order to validate the model and study the system's response to vacuum variation due to a pulse air leak the detachment (fall-off) of one teatcup was simulated; the teatcup was detached for 10, 20 and 30 seconds respectively. During the fall-off tests the rate of air flow into the system was measured by the means of a rotameter and the vacuum level was recorded. The experimental results were compared with the ones predicted by the model and it was concluded that the model accurately describes the response of the system.

Keywords: variable frequency drive, vacuum system model, teatcup fall-off test.

1 Introduction

The mechanical milking is achieved due to the vacuum applied to the teat, by the means of a teatcup. In order to limit the development of congestion and edema and provide relief to the teat from the milking vacuum, the pulsation principle is used (Mein *et al.*, 1987). As shown in Figure 1, vacuum is applied to the teat through the vacuum chamber (7) created inside the liner (2). The collapse of the teatcup liner (2)

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beneath the teat is achieved when air at atmospheric pressure is admitted into the pulsation chamber (5) of the teatcup (Fig. 1a); the liner opens, allowing the extraction of milk, when vacuum is applied to the pulsation chamber (Fig. 1b).

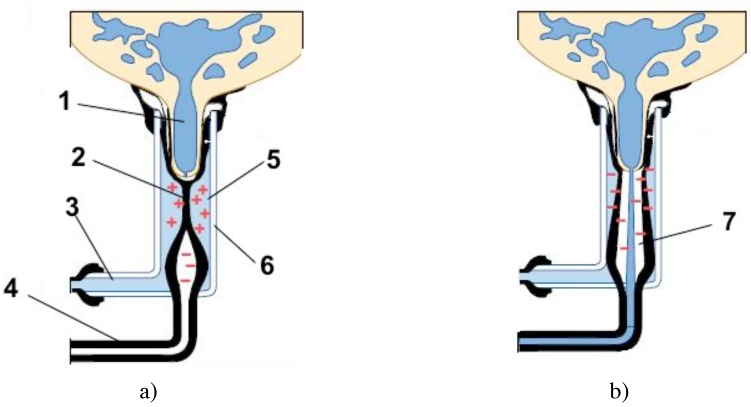


Fig 1. The principle of milk extraction (adapted from Dairy Processing handbook, 1995).
a-massage; b-milk extraction; 1-teat: 2-liner; 3-short pulse tube; 4-short milk tube; 5-pulsation chamber; 6-shell; 7-vacuum chamber.

Figure 2 presents the layout of a typical mechanical milking system (ISO 3918:2007), which contains a vacuum pump (2), driven by an electric motor (1); the vacuum pump creates vacuum into the vacuum pipeline (7), which is used for both the milk extraction and the pulsation of the liner. The vacuum level is regulated by the means of the vacuum regulator (4), placed downstream of the receiver. The vacuum pump is permanently operated at full capacity, providing a flow of air greater than the one entering the system through pulsators, claws, leaks. The difference between the air extracted by the pump and the necessary flow of air during milk extraction is compensated by the vacuum regulator, which opens to allow supplementary air to enter into the system when working vacuum increases above the desired level and closes when vacuum decreases below the necessary value; according to the ISO 5707:2007 standard the working vacuum should be maintained within ±2 kPa of the nominal vacuum.

The importance of vacuum level and stability is due to the fact that cows have a biological limit for a positive reaction to vacuum and exceeding it may lead to damage of the teat tissue or slipping of milking clusters off the teat, resulting in an extended milking time and in improper milking; vacuum fluctuations generated within the milking cluster may lead to direct bacterial penetration, thus causing mastitis (Pařilová *et al*., 2011).

In order to make the vacuum pump draw only the amount of air needed to maintain the desired vacuum level, the speed of the pump should be variable (as air flow depends on the pump speed); in this case no conventional regulator is needed to maintain the imposed vacuum during milking. The electric motor of vacuum pump is controlled by the means of a variable frequency driver (VFD). This solution has the potential to significantly reduce the energy consumption of the milking system; in a study conducted by Pazzona *et al*. (2003) energy savings between 24 and 87% were reported. It was concluded that, if the VFD controller is adjusted properly, it can meet or even exceed the vacuum stability recorded by the systems equipped with conventional regulators (Pazzona *et al*., 2003; Reinemann, 2005), the target being a receiver vacuum within ±2 kPa of the vacuum set point during normal milking (ISO 5707:2007).

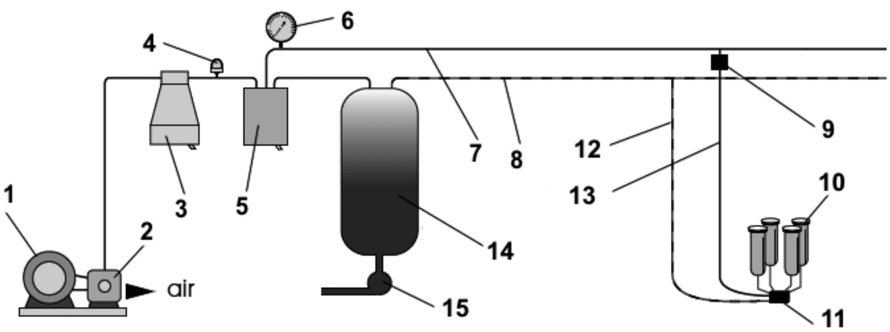


Fig. 2. Layout of a mechanical milking system.
1-electric motor; 2-vacuum pump; 3-interceptor; 4-vacuum regulator; 5-sanitary trap; 6-vacuum gauge; 7-permanent vacuum pipeline; 8-milk pipeline; 9-pulsator; 10-teatcup assembly; 11-claw; 12-long milk tube; 13-long pulse tube; 14-receiver; 15-milk pump.

The first stage of the study was aimed to validate the principle of the vacuum regulation by the means of the VFD controlled vacuum pump. In order to proceed to a more systematic approach of the problem in the second part of the paper a mathematical model of the vacuum system was developed and tested, based on the system's response to vacuum variation due to a pulse air leak - detachment (fall-off) of one teatcup.

2 Materials and Methods

A bucket type milking machine was tested and modeled; Fig. 3 presents the diagram of the milking system. The original system was equipped with a valve and spring type of vacuum regulator, placed on the pipeline connecting the interceptor (I) to the bucket (B); the electric motor (M) driving the vacuum pump (VP) was connected to the three phase power grid. A BRK pneumatic pulsator (P) was used to achieve the liner pulsation; the machine was equipped with four Boumatic R-1CX type teatcups. Artificial teats, manufactured according to the ISO 6690:2007 standard, were inserted into the teatcups. The vacuum pump provided an airflow $q=4.69 \cdot 10^{-3}$ m^3 s^{-1} at a speed of 1350 min^{-1}.

In order to use the VFD controller for driving the vacuum pump a Smartec SPD015AAsil absolute pressure sensor (T, fig. 3) was used to monitor the vacuum in the permanent vacuum line, providing the pressure signal for the VFD controller. The electric signal from the pressure sensor was fed to the data acquisition (DAQ) board by the means of a signal conditioning unit (SC).

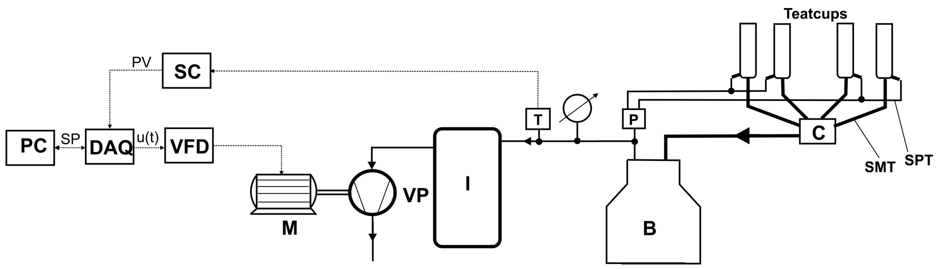


Fig. 3. Schematics of the tested milking system
DAQ-data aquision board; SC-signal conditioning unit; I-interceptor; VP-vacuum pump; M-electric motor; B-bucket; P-pulsator; SMT-short milk tube; SPT-short pulse tube; T-absolute pressure transducer; C-claw.

The data aquision board was USB 6009 (National Instruments), with a sample rate of 48 ksamples/s, four differential analog input channels and two analog output channels.

Based on the software running on the computer the entire system (DAQ board, VFD controller and computer) acts as a PID regulator for the vacuum level, for which the set point (SP) is the desired vacuum level and the process variable (PV) is the actual vacuum level in the vacuum pipeline. The controller calculates the output signal u(t), which is then used to command the VFD and adjust the running speed of the electric motor and vacuum pump. The PID controller output is given by the relation (Aström and Murray, 2008):

$$u(t) = K_p \cdot \left[e(t) + \frac{1}{T_i} \cdot \int e(t) \cdot dt + T_d \cdot \frac{de(t)}{dt} \right], \quad (1)$$

where the error signal is e(t) = SP-PV; K_P is the proportional gain, T_I is the integral time and T_d is the derivative time.

The PID controller was built with the help of the PID control toolbox from LabVIEW 7.1 and a virtual instrument was created in order to provide the control signal to the VFD. The control panel of the virtual instrument (Fig. 4) allowed the adjustment of the desired vacuum level (vacuum set point) and of the PID gains: proportional gain, integral time [min] and derivative time [min].

The output range of the PID controller was 0…5V, due to the characteristics of the data aquision board; an additional signal conditioning unit (not shown in Fig. 3) was used to obtain the 0…10V range imposed by the variable frequency drive.

An oscilloscope display allowed the visualization of the vacuum set point, system vacuum and output signal of the PID controller.

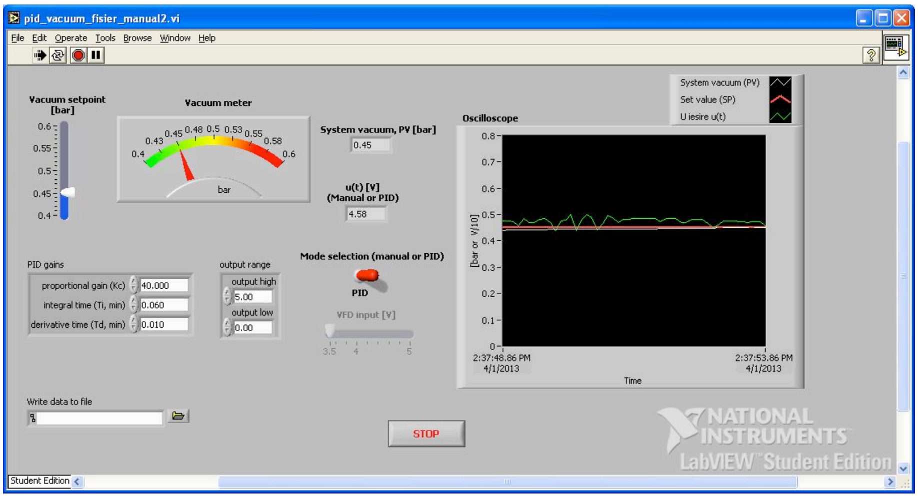


Fig. 4. The control panel of the virtual instrument

The variable frequency drive unit was VFD 007M43B (0.7 kW maximum power of the electric motor); the output frequency range was set to 0...60 Hz for a range of the analog comand signal comprised between 0 and 10V.

In order to establish the working parameters of the milking process (pulsation rate and ratio, duration of the phases), two additional Smartec SPD015Aasil absolute pressure sensors (not shown on the diagram in Fig. 3) were attached to the short pulse tube (SPT, Fig. 3) and short milk tube (SMT). The pulsation ratio was defined according to the specifications of the ISO 5707:2007 standard.

The Ziegler-Nichols tuning rules for the frequency response method were used; the disturbance was induced by changing the set point. After that the permanent vacuum values were recorded in a series of dry tests, performed for three vacuum levels: 0.35 bar, 0.40 bar and 0.45 bar (35, 40 and 45 kPa). In order to asses vacuum stability the results were compared, using the average value of the vacuum, the standard deviation and the standard error of the mean. Three tests were performed for each vacuum level and vacuum regulation method and the mean, standard error and standard error of the mean were calculated.

In order to evaluate whether there was a significant difference between the two pairs of data (the permanent vacuum levels recorded for two regulation methods) a statistical analysis was performed. The Kolmogorov-Smirnov test proved that data distribution was not normal; as a result, the Man Whitney rank sum test was performed; this test is a substitute for the two-sample t test when the samples are not normally-distributed populations (Panik, 2005). The analysis was performed with a demo version of the SigmaPlot 12.5 software.

The mathematical model of the vacuum system was developed assuming that the system is composed of a single air tank, provided with a vacuum pump port and an air-using port (Tan, 1992; Tan *et al.*, 1993), as shown in Fig. 5, where $\dot{m}_1$ represents the mass airflow rate of the vacuum pump and $\dot{m}_2$ is the mass airflow rate into the system.

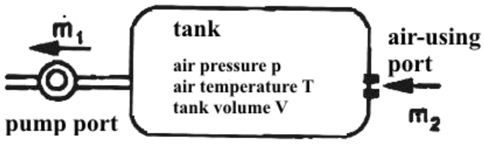


Fig. 5. Schematics of the milking system [5]

$\dot{m}_1$, $\dot{m}_2$-mass air flow rate

The following equations may be written [6]:

$$\frac{dM}{dt} = \dot{m}_2 - \dot{m}_1 = \dot{m}_2 - q \cdot \frac{M}{V} , \tag{2}$$

$$p = R \cdot T \cdot \frac{M}{V} , \tag{3}$$

where M is the mass of air in the air tank, V is the tank volume, q is the volumetric flow rate of the vacuum pump, R is the gas constant for air ($R=287\ J \cdot kg^{-1} \cdot K^{-1}$) and T is the air temperature [K].

Using equations (2) and (3) the transfer function of the system is (Tan *et al.*, 1995):

$$G(s) = \frac{p(s)}{\dot{m}_2(s)} = \frac{R \cdot T / q}{1 + s \cdot V / q} . \tag{4}$$

Fig. 6 presents the system response when the air flow rate increases due to the detachment of one teatcup: when the mass flow rate $\dot{m}$ increases by $\dot{m}_p$, the absolute system pressure p_n increases by p_p.

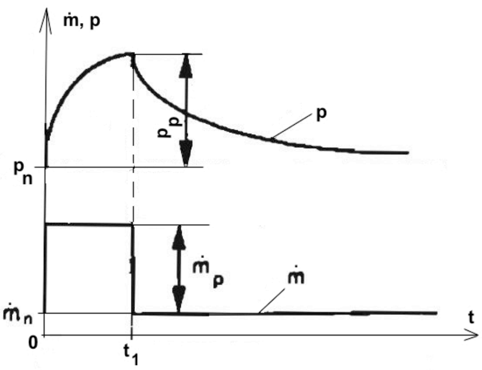


Fig. 6. Model response to mass airflow rate variation (Tan *et al.*, 1993)

p-absolute pressure; t_1-detachment duration.

The mass flow rate resulting from the pulse air leak $\dot{m}_p$ is (Tan *et al.*, 1993):

$$\dot{m}(s) = \frac{\dot{m}_p}{s} - \frac{\dot{m}_p}{s} \cdot e^{-t_1 \cdot s} . \tag{5}$$

Introducing equation (5) into equation (4) and applying the inverse Fourier transform finally leads to:

$$p(t) = \frac{R \cdot T}{q} \cdot \dot{m}_p \cdot \left[\Phi(t) - \Phi(t - t_1) - e^{-q \cdot t / V} + \Phi(t - t_1) \cdot e^{-q \cdot (t - t_1) / V}\right], \tag{6}$$

where Φ(t) is the step function, defined as follows:

$$\Phi(t) = \begin{cases} 0, & \text{if} \quad t < 0 \\ 1, & \text{if} \quad t \geq 0 \end{cases}. \tag{7}$$

For the milking system taken into account the singe tank volume (which includes the interceptor volume and the bucket volume) was $V=3.5 \cdot 10^{-2}$ m^3 and the air temperature was T=293 K.

In order to validate the model and study the system's response to vacuum variation due to a pulse air leak the detachment (fall-off) of one teatcup was performed; the teatcup was detached for 10, 20 and 30 seconds respectively. During the fall-off tests the rate of air flow into the system was measured by the means of a rotameter and the evolution of the vacuum level was recorded using the pressure sensor (T, Fig. 3).

The air flow rate into the system during the fall-off test was $\dot{m}_p = 7.6 \cdot 10^{-5}$ $kg \cdot s^{-1}$ (average value).

The steady state gain K of the model and the time constant τ were calculated with the relations (Tan *et al.*, 1993):

$$K = \frac{R \cdot T}{q}, \quad \tau = \frac{V}{q}. \tag{8}$$

For the milking system taken into account the following values were obtained:

- $K=1.79 \cdot 10^5$ $kPa \cdot s \cdot kg^{-1}$;
- τ=7.47 s.

Using the experimental data the system steady state gain K_s and the time constant τ_s were evaluated. The system steady-state gain was calculated with the formula:

$$K_s = \frac{\Delta p}{\dot{m}_p}, \tag{9}$$

where Δp is the vacuum drop when the teatcup is detached.

The time constant τ_s was considered to be the time required for the output vacuum to reach 63.2% of the final value when the teatcup was detached.

3 Results and Discussion

3.1 Vacuum stability

In order to tune the PID controller using the Ziegler-Nichols tuning rules for the frequency response method, the integral time was set at 10000 and the derivative time was set to 0; the proportional gain was adjusted until the oscillations were sustained and had a constant amplitude. Finally, the critical gain was $K_c = 68$. The critical period T_c was measured using the recorded vacuum signal; it was established that the critical period was $T_c = 7.53 \pm 0.46$ s. The PID gains were then calculated using the formula presented in Table 1 (Aström and Murray, 2008).

Table 1. Controller parameters for the Ziegler-Nichols frequency response method

Controller type	K_P	T_i	T_d
P	$0.5 \cdot K_c$	-	-
PI	$0.4 \cdot K_c$	$0.8 \cdot T_c$	-
PID	$0.6 \cdot K_c$	$0.5 \cdot T_c$	$0.125 \cdot T_c$

For the case of the PID controller, the following gains were obtained: $K_P = 40$, $T_i = 4.76$ s (0.062 min), $T_d = 0.941$ s (0.015 min).

The results referring to the working parameters of the system and vacuum stability are shown in Tables 2 and 3.

Table 2. Working parameters of the milking system

Regulation method	Item	Vacuum level [kPa]		
		35	40	45
Vacuum regulator	Pulsation rate [cycles/min]	48.4±0.231	51.9±0.266	55.9±0.200
	Pulsation ratio [%]	55.1/44.9	53.7/46.3	53.3/46.7
	Duration of b phase* [%]	44.9±0.137	41.98±0.362	39.74±0.270
	Duration of d phase** [s]	0.42±0.005	0.387±0.003	0.343±0.003
PID controller	Pulsation rate [cycles/min]	48.9±0.352	52.2±0.500	56.4±0.167
	Pulsation ratio [%]	54.6/45.4	53.8/46.2	53.2/46.8
	Duration of b phase [%]	44.02±0.352	41.21±0.405	39.40±0.113
	Duration of d phase [s]	0.42±0.006	0.387±0.012	0.337±0.003

Notes: *at least 30% of the cycle duration; **at least 0.15 s.

The results presented in Table 2 show that the working parameters of the system (pulsation rate and ratio, duration of the cycle phases) did not change significantly when passing from the classical method for vacuum regulation (based on the use of a valve type regulator) to the new one, based on the adjustment of the vacuum pump speed. A slight increase of the pulsation rate was however noticed when the second method was used, but the differences did not exceed 1%; the slightly higher pulsation rate resulted in a shorter b phase when the PID controller was used for vacuum regulation, but the requirements of the ISO 5707 standard were fulfilled.

An analysis of the individual values of the permanent vacuum showed that, for the both methods, the working vacuum was maintained within ±2 of the nominal vacuum kPa, in accordance with the requirements of the ISO 5707 standard.

The results presented in Table 3 show that the use of the PID controller method for vacuum regulation led to lower standard deviations and standard errors of the mean than the ones recorded when the classical vacuum regulator was used, proving a better vacuum stability.

The statistical analysis of the results, performed by the means of the Man Whitney rank sum test (SigmaPlot ver. 12.5, demo), confirmed that, for each set value of the vacuum level (35, 40 and 45 kPa, respectively) there were significant differences between the two sets of data.

Table 3. Results regarding vacuum stability

Regulation method	Item	Vacuum level (SP) [kPa]		
		35	40	45
Vacuum regultor	mean vacuum level, $\bar{x}$* [kPa]	34.417	39.462	44.398
	standard deviation, S [kPa]	0.202	0.230	0.226
	standard error of the mean, $S_{\bar{x}}$** [kPa]	0.0142	0.0162	0.0159
PID controller	mean vacuum level, $\bar{x}$ [kPa]	34.514	39.381	44.580
	standard deviation, S* [kPa]	0.172	0.194	0.186
	standard error of the mean, $S_{\bar{x}}$** [kPa]	0.0121	0.0137	0.0131

Notes: *for 200 recorded values; ** $S_{\bar{x}} = S/\sqrt{n}$

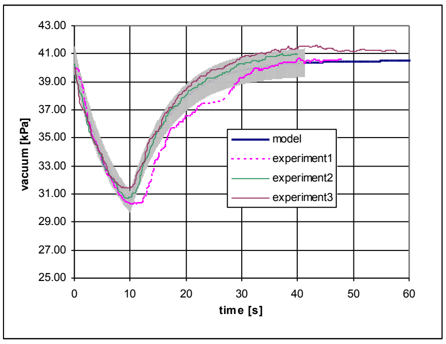
3.2. Vacuum system model

Fig. 7 presents the experimental results of the fall-off tests; the model data ("model") and data from three experimental replicates ("experiment 1", "experiment 2", "experiment 3") are shown on each chart, with the ±2.5% y errors bars superposed over the model curve.

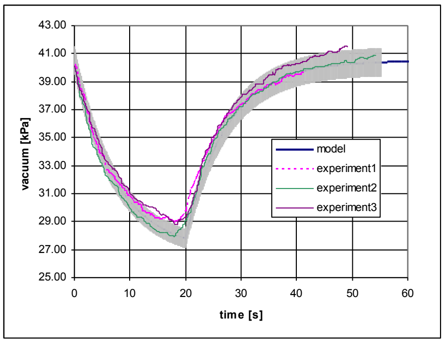
The tests clearly show that there are only small differences between model and experimental data and that the curves corresponding to the experimental data follow closely the theoretical curves predicted by the model, the majority of the experimental data being within the ±2.5% variation domain.

Table 4 presents the results concerning the steady-state gain and time constant obtained from the experimental results; the experimental steady-state gain is with 9% lower than the value given by the model and the time constant of the system is with

20% lower than the value predicted by the model.



a)



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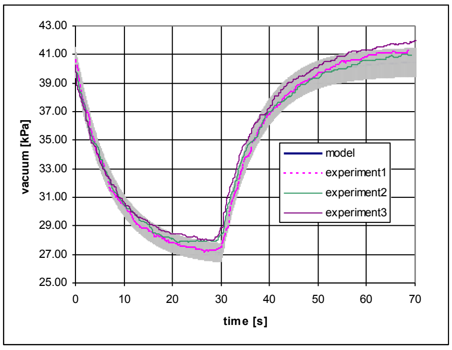

c)

Fig. 7. Experimental and model data

a) 10 s detachment of the teatcup;
b) 20 s detachment of the teatcup;
c) 30 s detachment of the teatcup.

Table 4. Experimental results for the time constant and steady-state gain

Teatcup detachment time [s]	Item	
	$K_s \cdot 10^{-5}$ [kPa·s/kg]	τ_s [s]
10	1.34	4.72
20	1.72	5.7
30	1.82	7.6
Average	1.63±0.146	6.00±0.845

The inaccuracy of the predicted time constant may be due to the assumptions that air is a perfect gas and that the system is isothermal, with only small variations of the air temperature (Tan, 1992; Tan *et al.*, 1993). If the process is considered adiabatic (Tan *et al.*, 1993; Tan *et al.*, 1995), the time constant is calculated with the relationship:

$$\tau = \frac{V}{\gamma \cdot q}, \tag{10}$$

where γ=1.4 is the heat capacity ratio of air.

As a result the time constant of the model becomes τ=5.33 s, a value which is much closer to the average value of 6 s given by the experiments (12,5% lower).

4 Conclusions

The permanent vacuum level in a bucket milking machine was adjusted by the means of a PID regulator, using a variable frequency driver in order to power the electrical motor driving the vacuum pump. The PID regulator, implemented using the NI LabView capabilities, was aimed to maintain a constant vacuum level.

The PID regulator was tuned in order to establish the PID gains using the Ziegler-Nichols frequency response method.

A series of dry tests were performed, at different vacuum levels, in order to compare the two methods of vacuum regulation (using a mechanical vacuum regulator and a PID regulator, respectively); the tests proved that vacuum regulation by the means of the PID controller has the potential to replace the classical method of regulation as it did not adversely affect the working parameters of the system, while achieving better results regarding the stability of the permanent vacuum.

As the principle of the vacuum regulation by controlling the vacuum pump speed was confirmed the next step was to develop a mathematic model of the milking system in order to proceed to a more rigourous analysis of the system. As a first step a simplified physical model was adopted, considering the mechanical milking system as first order dynamic system with a single air tank, provided with a vacuum pump port and an air-using port.

In order to validate the model and study the system's response to vacuum variation due to a pulse air leak the detachment (fall-off) of one teatcup was simulated; the teatcup was detached for 10, 20 and 30 seconds respectively. During the fall-off tests the rate of air flow into the system was measured by the means of a rotameter and the vacuum level was recorded.

As a result of the tests it was concluded that the developed model is accurate, the majority of the experimental values being comprised within the ±2.5% range of the model.

However, the assumption that the process is isothermal led to a relatively high difference between the predicted value of the time constant and the value obtained during the experiments. This difference diminished if the adiabatic hypothesis was considered.

Developing a more complex model of the milking system is taken into account for a future work, aiming to obtain more accurate predictions.

References

1. Aström, K. J. and Murray, R. M. (2008). Feedback Systems: An Introduction for Scientists and Engineers. Princeton University Press (available on-line from http://www.cds.caltech.edu/~murray/amwiki).
2. Bade, R. D., Reinemann, D. J., Zucali, M., Ruegg, P.L. and Thompson P.D. (2009). Interactions of vacuum, b-phase duration and liner compression on milk flow rates in dairy cows. Journal of Dairy Science, 92, p. 913-921.

3. Delta Electronics Inc. (2008). VFD-M User manual (available on-line from http://www.delta.com.tw/product/em/drive/ac_motor/download/manual/VFD-M-D_M_EN_20090506.pdf).

4. ISO 3918:2007. Milking machine installations – Vocabulary. International Organization for Standardization, Geneva, Switzerland.

5. ISO 5707:2007. Milking machine installations - Construction and performance. International Organization for Standardization, Geneva, Switzerland.

6. ISO 6690:2007. Milking machine installations – Mechanical tests. International Organization for Standardization, Geneva, Switzerland.

7. Mein, G.A., Williams, D.M. and Thiel, C.C. (1987). Compressive load applied by the teatcup liner to the bovine teat. Journal of Dairy Research, 54, p. 327-337.

8. Panik, M.J. (2005). Nonparametric statistical techniques. In Advanced statistics from an elementary point of view, ch. 13, 569-608. Burlington: Elsevier Academic Press.

9. National Instruments. LabVIEW 7.1. Austin, Texas: National Instruments.

10. Pařilová, M., Stádnik, L., Ježková, A. and Štolc, L. (2011). Effect of milking vacuum level and overmilking on cows' teat characteristics. Acta Universitatis Agriculturae et Silviculturae Mendelianae Brunensis, LIX (23), 5, p. 193-202.

11. Pazzona, A., Murgia, L., Zanini, L., Capasso, M.and Reinemann, D.J. (2003). Dry test of vacuum stability in milking machines with conventional regulators and adjustable speed vacuum pump controllers. Presented at the ASAE Annual International Meeting, Las Vegas, Nevada. ASAE Paper 033013 (available on-line from: http://milkquality.wisc.edu/wp-content/uploads/2011/10/dry-tests.pdf).

12. Reinemann D. J. (2005). The history of vacuum regulation technology. Proceedings of the 44th annual meeting of the National Mastitis Council. Orlando, Florida, 16-19 January (available on-line from http://nmconline.org/articles/VacuumHistory.pdf).

13. Systat software. SigmaPlot ver. 12.5. San Jose, California: Systat software, Inc.

14. Smartec BV. Datasheets of pressure sensors. Breda, Netherlands: Smartec BV (available on-line from http://www.smartec-sensors.com/assets/files/pdf/Datasheets_pressure_sensors/SPD015AAsilN.pdf).

15. Tan, J. (1992). Dynamic characteristics of milking machine vacuum systems as affected by component sizes. Transactions of the ASABE, 35(6), p. 2069-2075.

16. Tan, J., Janni, K.A. and Appleman, R.D. (1993). Milking system dynamics 2-Analysis of vacuum systems, Journal of Dairy Science, 76, p. 2204-2212.

17. Tan, J. and Wang, L. (1995). Finite-order models for vacuum systems, Transactions of the ASABE, 38(1), p. 283-290.

18. Tetra Pak (1995). Dairy Processing handbook. Lund, Sweden: Tetra Pak Processing Systems AB.