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Effect of altitude and vacuum pressure on flow rate of vacuum pumps on milking machines driven by gasoline engine and a generator

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Abstract. The objective of this study was to compare the performances of two vacuum pumps driven by an internal combustion (gasoline) engine (Vacuum Pump 1) and a generator powered electrical motor (Vacuum Pump 2) under different altitude and vacuum pressures. The vacuum pumps delivering a flow rate of 350 l min^{-1} at 50 kPa vacuum pressure were tested, which are commonly used in bucket type milking machines. Atmospheric pressures, maximum vacuum pump pressures, and air flow rates at milking pressures (38–50 kPa) were measured at altitudes from 0 to 2,000 m with 200 m increments. Maximum pump pressure reduced by 3.8, 11.3, and 19.9% for Vacuum Pump 1 at altitudes of 400, 1,200, and 2,000 m, respectively whereas Vacuum Pump 2 had 4.4, 12.3, and 20.4% less maximum pressure at the same altitudes. Air flow rate (457.7 l min^{-1}) of Vacuum Pump 1 at the sea level at 38 kPa working pressure reduced by 22.7% at the altitude of 2,000 m. The air flow rate reduced more (28.1%) at the operating pressure of 50 kPa for Vacuum Pump 1 at 2,000 m, compared to the sea level. Similarly, for Vacuum Pump 2, the measured flow rate at 38 kPa showed 19.1% reduction at 2,000 m while at 50 kPa the air flow rate reduced 26.4%, corresponding to 352.3 l min^{-1}. Differences in the air flow rates of vacuum pumps 1 and 2 under different vacuum pressures were insignificant ($P > 0.05$). However, the effect of altitude and vacuum pressure on measured air flow rates was significant for each pump at 5% level. The regression equations were also obtained for atmospheric pressure-altitude, maximum pump pressure-altitude, air flow rate-altitude, and air flow rate-pump vacuum-altitude. High determination coefficients that were found for these relationships suggest that pressure setting can be accurately done as the altitude at which milking needs to be changed without suffering from air flow rate during milking with bucket type machines.

Key words: Milking machine, vacuum pump, gasoline engine, generator, altitude, pump pressure, air flow rate.

INTRODUCTION

Vacuum is simply described as the air pressure less than atmospheric pressure (Chambers, 2004). Since the air in the atmosphere constantly applies pressure on earth due to the weight of the air, vacuum can only be created using vacuum pumps. Vacuum pumps are used in many different industrial areas and also used in animal production in the milking machines. The milking process is accomplished due to the vacuum (negative pressure) created in the pump.

The pressure needed in the milking unit may be from 36 kPa to 50 kPa depending on the animal type and the height of the milk transportation line. The processes such as sucking the milk from the animals, transportation of the milk to the bucket or the storage tank, and carrying the cleaning fluids through the conduits are done using the vacuum generated by the vacuum pump in the milking system (Unal, 2013).

Piston pumps, turbine type pumps, and vane type pumps are usually used as vacuum pumps in milking machines. In recent years, the use of piston pumps has been abandoned and turbine types have limited usage. Thus, the most common type of vacuum pump used for milking is the rotary/pallet type pumps (Mein et al., 1994; Southern California Edison, 2005; Unal, 2013).

Vane type pumps usually have 4 to 6 vanes, rotating around the rotor of the pump (Mein et al., 1995; Bilgen & Oz, 2006; Unal, 2013). The pump is usually powered by an electrical motor while in the absence of electricity a generator, internal combustion engine or power take-off of a tractor is also used.

The pressure that can be delivered by a vacuum pump can be determined either by using the pump characteristics curves or experimentally for a given vacuum pump. Literature was not abundant on the relationships among the flow rate, varying altitudes and pressure values in the milking machines. The performance of a vacuum pump is mainly affected by the altitude. Altitude changes the atmospheric pressure, resulting in reducing vacuum pressure that can be accomplished by a vacuum pump. While perfect vacuum cannot be obtained, in some industrial applications vacuum pumps are expected to evacuate at least 95% of the air in a tank and in some medical applications this rate needs to be greater than 99.9% (Ohio Medical Corporation, 2015). However, the efficiency of a vacuum pump may be much lower depending on the design, sealing, and operation conditions. In order to correct the performance of a vacuum pump, readily available specification sheets may be used (Anver Corporation, 2002). But, since the efficiencies of vacuum pumps differ, the maximum available flow rate and vacuum pressure of a specific vacuum pump needs to be determined experimentally. Another factor affecting the vacuum pump performance is the air temperature. The effect of air temperature on measured vacuum pressure can be corrected, but usually is neglected (Chilvers & Love, 1986). Therefore, this study focuses on a specific milking machine and attempts to determine the behaviour of the vacuum pump of the milking machine in the field conditions.

In milking, the capacity of a vacuum pump mainly depends on the number of milking units and altitude at which the milking takes place. Other factors affecting the milking pump capacity are the type of cleaning unit, automatic cluster remover, pulsator type, and air leaks in the system (Chilvers & Love, 1986; Unal, 2013; TS ISO 5707, 2014).

Small scale dairy production is generally dominant in underdeveloped or developing countries. For instance, the number of bucket type milking machines in Turkey was 292,405 in the year 2015 whereas the number of parlor milking systems was 9,744 (TSI, 2015) Eighty per cent of the dairy farms is small size (1–50 cows), 17% is mid-size (50–100 cows), and only 3.5 is big size farms (> 100 cows) (TSI, 2015). Most small enterprises use bucket type milking machines driven by electrical motors and encounter problems due to risk of electricity cut offs or are unable to use electricity in areas far from villages. Furthermore, there are many farmers living at mountainous areas with altitudes up to 2,000 m causing reduced air flow rates in the vacuum pumps.

Literature did not reveal abundant information on experimental results on the performance of bucket type milking machines at different vacuum pressures as a result of altitude change. In this study, two vacuum pumps were considered driven by a gasoline engine and a generator for areas where electricity may be out of reach for various reasons. The objectives of this study were to:

1) measure and compare the air flow rate capacities of two milking machines, i.e. gasoline engine operated (Vacuum Pump 1)and generator operated (Vacuum Pump 2) vacuum pumps, both bucket type, at altitudes ranging from 0 to 2,000 m and milking pressures from 38 to 50 kPa,

2) determine the number of milking units that can be used at different altitudes and pressure settings.

MATERIALS AND METHODS

Two vacuum pumps with the same air flow capacity were used in the study. The pumps used in the experiments are usually used on bucket type milking machines. The first vacuum pump was driven by an internal combustion (gasoline) engine (VP1) while the second one was used with a generator (VP2). Power transmission was done using a pulley in both vacuum pumps. Technical specifications of the vacuum pumps and the power sources are given in Table 1.

Table 1. Technical specifications of the vacuum pump, generator and gasoline engine

Feature	Value
Vacuum pump	
Pump type	Oil type, fibre vane pump
Vane number and vane dimensions (LxWxT)	4 / 120 x 45 x 5 mm
Stator diameter and length	∅ 110 x 120 mm
Rotor diameter and length	∅ 92 x 120 mm
Pump inlet and outlet diameters (mm)	∅ 34 / ∅ 27
Pump air capacity	350 l min^{-1}
Electrical engine	
Power (Single Phase)	1.1 kW
Voltage, Current, Frequency, Cycle	220 V, 8.0 A, 50 Hz, 1,400 rpm
Generator	
Power (Single Phase)	3.0 kVA
Voltage, Current, Frequency, Cycle	231 V, 13.0 A, 50 Hz, 3,000 rpm
Gasoline engine	
Engine type	Single cylinder, 4 stroke, air-cooled
Maximum power	3.5 HP (at 3,600 rpm)
Fuel tank capacity	1.8 l
Belt pulley unit	
Electric engine and pump pulley diameters (Generator)	∅130 / ∅120 mm
Engine and pump pulley diameters (Gasoline Engine)	∅100 / ∅130 mm
V belt number x width x length	1 x 13 mm x 875 mm

For the ease of operation, both pumps were mounted on a common frame (Fig. 1) and installed at the back of a pick-up truck. All measurements were done with the vacuum pumps on the truck during the testing.

Air flow rates were measured at different altitudes with 200 m increments starting at the sea level up to 2,000 m. The experiments were conducted in Bursa Province, started in Mudanya town at sea level (2.0 m) and ended near the top of Uludag Mountain (2,012 m).

The measurements were done at vacuum pressures from 36 to 52 kPa with 2 kPa increments. As a result, the measurements were done at 11 different altitudes and 9 different vacuum pump pressures. The pressure range used in this study was selected based on the animal species to be milked. The pressure requirement for sheep milking is about 36 kPa and greater pressures are needed for goats, cows, and water buffalo. The second reason for choosing the pressure range of 36 to 52 kPa is that pressure may go up to 50–52 kPa in high rise milking machines and systems (Mein et al., 1995; Unal, 2013).

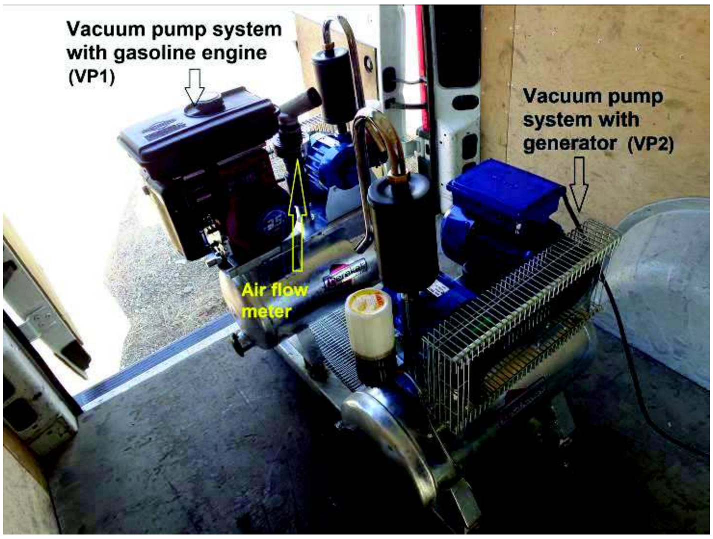


Figure 1. VP1 and VP2 driven by gasoline engine and generator, respectively.

Before the experiments, an orifice type manuel flow meter (AM 3000) was installed on the inlet line of the vacuum pump to make flow rate measurements, which had a capacity of 3,000 l min^{-1}. Vacuum changes of the pump were monitored using a digital vacuum meter (DVPM-01) with 0.1 kPa precision, mounted on the flow meter via a hose.

At each elevation, first the maximum pump pressure was measured by closing all air ports on the flow meter. Then, the air flow rate was measured at the pressure levels that are of interest. The measured parameters were the altitude, gage atmospheric pressure, relative humidity, and air temperature. Altitude and atmospheric pressure were measured using a digital device (OREGON RA123) that can measure altitudes up to 10,000 m with 1 m precision. Atmospheric pressure was measured in hPa and was converted to kPa (1 hPa = 0.1 kPa). Relative humidity and temperature were measured by using a thermo-hygrometer with 0.1 °C and 1% precision, respectively.

Vacuum pumps were set to 50 kPa (TS ISO 5707 and TS ISO 6690 standards) and the pump rotational speed was measured using a digital scope with 1.0 rpm precision.

The rotational speed of the gasoline engine was adjusted to be the same as the generator to compare the results of two vacuum pumps.

Attention was paid to make measurements at exactly 200 m increments from the sea level. However, it was not always possible to stop at the exact altitude desired for the measurements. The vehicle carrying the test units could be stopped within –13 m and + 12 m deviations from the targeted altitude.

The regression equations were found for the relations between altitude and atmospheric pressure, altitude and maximum pump pressure, and maximum vacuum pump pressure and gage atmospheric pressure to determine the appropriate operating conditions for the milking machines at different altitudes.

Maximum number of milking units was calculated using the air flow rates obtained at each operating condition (Billon, 2004; Bilgen & Oz, 2006; TS ISO 5707, 2014; TS ISO 6690, 2014). The factors used for this purpose were reserved capacity (80 + 25n), air flow requirement of milking unit (35n), regulation loss (35 l min^{-1}), 1st subtotal, correction factor based on altitude (0–300, 300–700, 700–1,200, 1,200–1,700, and 1,700–2,200 m), 2nd subtotal, air leak ((2nd subtotal/0.95)*0.05), total air capacity of vacuum pump at each altitude (2nd subtotal + air leak) (l min^{-1}) where n is the number of milking units.

The experiment data were analysed using a factorial with completed randomized design and three replicates ± standard error (SE). The results were processed by the MINITAB (Version 14, University of Texas, Austin, USA) and MS-Excel software programs. One way analysis of variance and LSD test MSTAT_C (Version 2.1., Michigan State University, USA) software program were used to analyse the results. Differences were considered significant at $P < 0.05$, unless otherwise specified.

RESULTS AND DISCUSSION

The altitude and the atmospheric pressure values were measured first at targeted altitudes. The measurements could not be done exactly at 200 m and its multiples during the experiments due to the inconveniences of the mountain road conditions. The difference between the desired and measured altitudes (Fig. 2) was about ± 1–2% and was assumed to be negligible in the calculations.

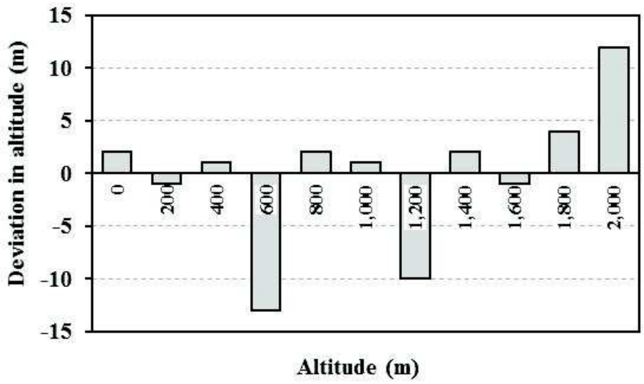


Figure 2. Deviations from the desired altitudes at the measurement locations.

Measurements started in the morning about 10.00 am with 27.7 °C air temperature, rising up to 30.6 °C at about noon at the altitude of 600 m. Then the air temperature kept decreasing with 16.3 °C at 07:00 pm at the altitude of 2,000 m. Relative humidity was 52% at the sea level while it was 31% at the highest point of the measurements. Fig. 3 shows the measured air temperature and relative humidity readings during the experiments. These values were reported to give a general idea about the test conditions in this paper.

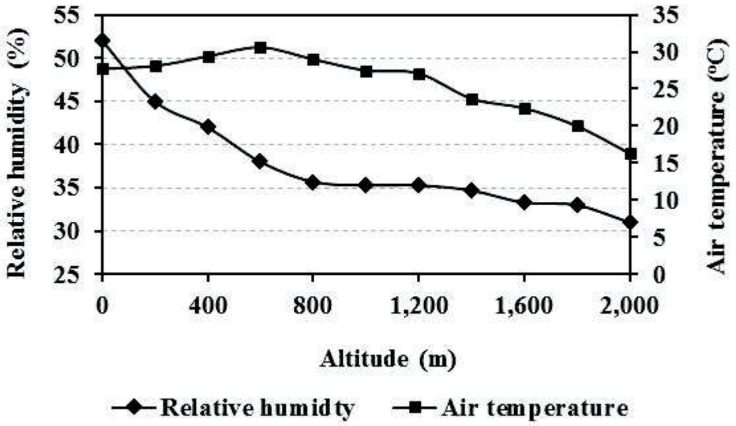


Figure 3. Measured relative humidity and air temperature as a result of altitude change.

Measured atmospheric pressure was measured to be 1006.9 hPa (100.69 kPa) at sea level and linearly decreased down to 793.6 hPa (79.36 kPa) at about 2,000 m (Fig. 4). It was calculated that atmospheric pressure decreased by 4.6, 9.2, 13.0, 17.1, and 21.2 %, respectively at 400, 800, 1,200, 1,600, and 2,000 m, compared to the sea level. Obviously it was not really necessary to measure the pressure as a function of altitude in this study since the same data could be obtained by using the universal physical rules. This evaluation was done not to confirm the governing physical rules but to verify the accuracy of the experimental devices and methods used in the study.

According to the measured data, the atmospheric pressure linearly varies with the altitude, as also well-known from the literature (Chambers, 2004). Based on experimental results, the dependence of atmospheric pressure on altitude could be calculated by using Eq. 1:

$$P_{atm} = 100.29 - 0.0106H \quad (R^2{:}0.998) \qquad (1)$$

where: P_{atm} – atmospheric pressure (gage pressure), kPa; H – altitude, m.

The linearity is very high between the altitude and the atmospheric pressure with a determination coefficient of 0.998, showing that Eq. 1 could be used to calculate the atmospheric pressure as function of altitude with high accuracy.

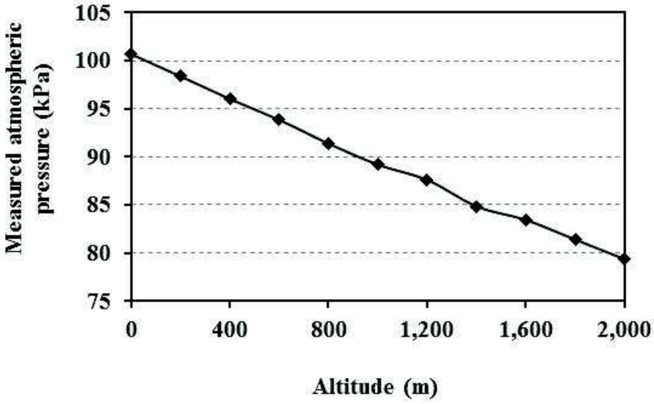


Figure 4. Measured atmospheric pressure as affected by the altitude.

Maximum pressures of vacuum pumps were given in Table 2 with 400 m increments up to 2,000 m. Although VP2 had higher measured vacuum pressures at all elevations, the difference between the two vacuum pumps was not significant ($P > 0.05$) except for altitudes of 0 and 1,600 m.

Table 2. Maximum pressure changes of vacuum pumps at different altitudes (DF = 11–24, F = 446.19, P < 0.05)

Altitude (m)	Maximum vacuum pump pressure (kPa)	
	VP1	VP2
0	94.3 ± 0.3^{b}	95.3 ± 0.1^{a}
400	90.7 ± 0.6^{c}	91.0 ± 0.3^{c}
800	86.7 ± 0.1^{d}	86.6 ± 0.1^{d}
1,200	83.7 ± 0.1^{e}	83.5 ± 0.1^{e}
1,600	79.3 ± 0.1^{g}	80.3 ± 0.7^{f}
2,000	75.6 ± 0.0^{h}	75.8 ± 0.4^{h}

The relationships between the altitude and the maximum vacuum pump pressure for VP1 and VP2 are given in Fig. 5, showing that maximum pump pressure decreases linearly with increasing altitude. The greatest vacuum pressure for VP1 was found at sea level with 94.3 kPa and the smallest pressure was 75.6 kPa at an altitude of 2,000 m. Maximum pump pressure decreased by 3.8, 8.0, 11.3, 15.9, and 19.9 % at altitudes of 400, 800, 1,200, 1,600, and 2,000 m, respectively. For VP2, maximum and minimum pump pressures were 95.2 and 75.8 kPa, respectively at sea level and at 2,000 m. The pressure dropped by 4.4, 9.0, 12.3, 15.6, and 20.4%, respectively at 400, 800, 1,200, 1,600, and 2,000 m, compared to sea level.

The relationship between the maximum pressures of the vacuum pump (P_{pmax}, kPa) and altitude was given in Eq. 2:

$$P_{pmax} = 94.6 - 0.0094H \quad (R^2{:}0.992) \qquad (2)$$

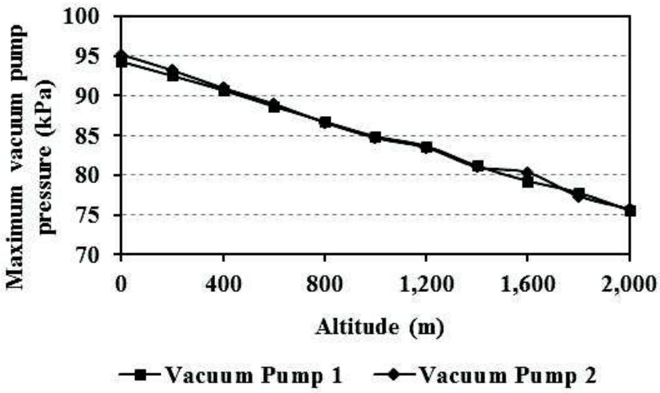


Figure 5. Maximum pressure and altitude relationships of VP1 and VP2.

Maximum vacuum pressures and true air pressure relationships were shown in Fig. 6 and can be calculated using Eq. 3:

$$P_{pmax} = 5.49 + 0.888P_{atm} \quad (R^2{:}0.992) \qquad (3)$$

Therefore, maximum vacuum pump pressure can be calculated accurately using measured atmospheric pressure due to high determination coefficient.

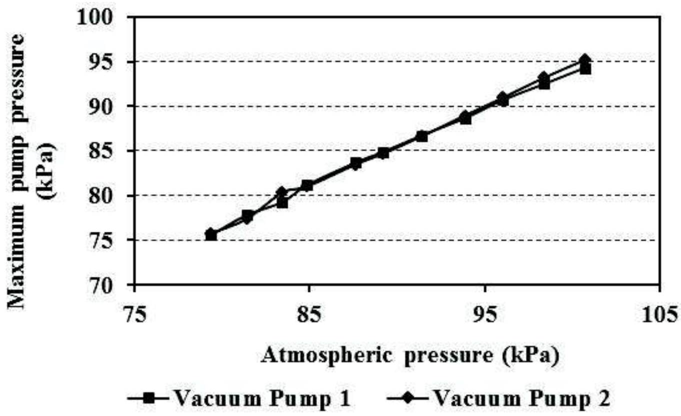


Figure 6. Maximum pressure and true air pressure relations of VP1 and VP2.

Air flow rates of vacuum pumps from 0 to 2,000 m at different vacuum levels were given in Table 3. The air flow rate of VP2 was greater than that of VP1 at a given altitude and vacuum pressure. The difference between the two pumps was found to be statistically significant at each altitude and vacuum level ($P < 0.05$). Also, the air flow rate decreased with increasing vacuum pressure at a given altitude.

Table 3. Air flow rates of vacuum pumps at different altitudes (means ±SE)

Altitude (m)	Vacuum pressure (kPa)	Air flow rate ($l\ min^{-1}$)		Statistically data
		VP1	VP2	
0*	38	458 ± 2.6^b	466 ± 1.2^a	DF = 7–16
	42	412 ± 2.2^d	423 ± 0.3^c	F = 829.26
	46	373 ± 1.9^f	385 ± 0.6^e	P < 0.05
	50	336 ± 2.1^h	352 ± 0.7^g	
400	38	436 ± 1.7^b	452 ± 2.6^a	DF = 7–16
	42	389 ± 1.9^d	406 ± 1.2^c	F = 668.57
	46	349 ± 1.3^f	367 ± 2.9^e	P < 0.05
	50	313 ± 1.2^h	336 ± 1.5^g	
800	38	410 ± 1.2^b	434 ± 2.2^a	DF = 7–16
	42	371 ± 1.2^d	389 ± 3.3^c	F = 430.77
	46	332 ± 2.0^f	349 ± 3.3^e	P < 0.05
	50	296 ± 1.8^h	319 ± 2.2^g	
1,200	38	388 ± 1.8^b	415 ± 2.2^a	DF = 7–16
	42	346 ± 1.9^d	367 ± 1.2^c	F = 686.54
	46	310 ± 2.9^f	329 ± 1.9^e	P < 0.05
	50	276 ± 0.9^h	297 ± 0.9^g	
1,600	38	369 ± 2.3^b	395 ± 0.9^a	DF = 7–16
	42	331 ± 1.5^d	348 ± 1.7^c	F = 633.10
	46	289 ± 0.7^f	310 ± 1.2^e	P < 0.05
	50	258 ± 3.7^h	278 ± 1.2^g	
2,000	38	351 ± 2.4^b	377 ± 1.8^a	DF = 7–16
	42	312 ± 2.3^d	334 ± 2.9^c	F = 507.74
	46	275 ± 2.0^f	291 ± 1.9^e	P < 0.05
	50	242 ± 1.8^h	259 ± 1.2^g	

*A separate statistical LSD test was conducted for each altitude. Results refer to %5 confidence level.

Air flow rate values of the vacuum pumps at different pump operating pressures and altitudes are given in Fig. 7. Air flow rate decreased linearly with increased vacuum pressure setting and altitude. When VP1 was set to 38 kPa at the sea level, the measured flow rate was 458 $l\ min^{-1}$ whereas the flow rate decreased to 397 $l\ min^{-1}$ and 351 $l\ min^{-1}$, respectively at 1,000 and 2,000 m. When the pressure setting was increased to 50 kPa, the measured air flow rates were 336, 287, and 242 $l\ min^{-1}$, respectively at 0, 1,000, and 2,000 m. Similar patterns were observed for VP2 with greater flow rates compared to VP1. For instance, the flow rates at 50 kPa were 352, 311, and 259 $l\ min^{-1}$ at 0, 1,000, and 2,000 m, respectively. Measured flow rates showed significant reductions as a result of the combined effect of increased vacuum pressure and altitude.

Standard vacuum is considered to be 50 kPa in milking operations (Mein et al., 1994 and 1995; TS ISO 5707, 2014; TS ISO 6690, 2014). As shown in Fig. 7, a & 7, b, linear decrease occurred in the flow rates in both vacuum pumps as the altitude was increased. Eqs 4 & 5 were derived from these data enabling the calculation of flow rate as a function of altitude:

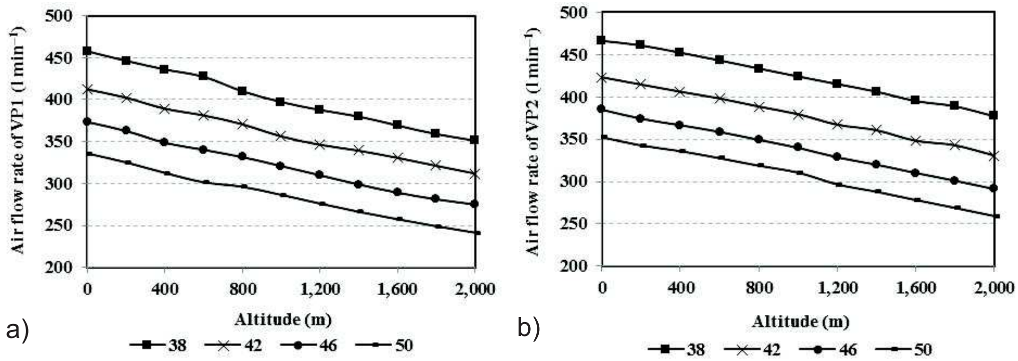


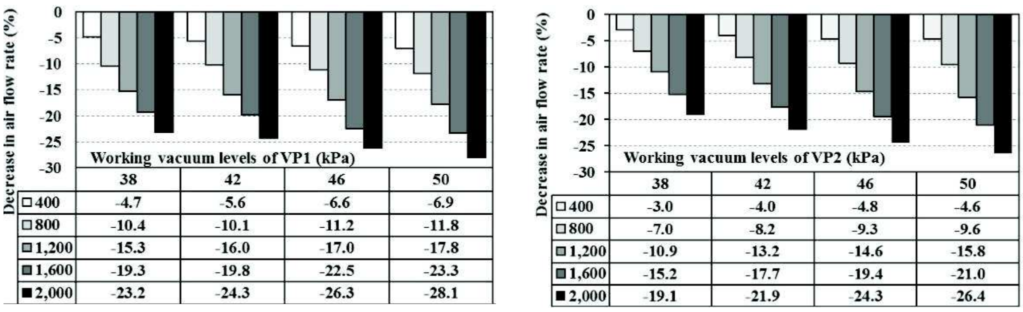
Figure 7. The effect of altitude on air flow rate of vacuum pumps at pressure range of 38–50 kPa for VP1 and VP2.

$$Q_{vp1} = 333 - 0.0469H \quad (R^2\text{: } 0.997) \tag{4}$$

$$Q_{vp2} = 354 - 0.0470H \quad (R^2\text{: } 0.997) \tag{5}$$

where: Q_{vp1}, Q_{vp2} – air flow rates of VP1 and VP2, respectively, at a vacuum pressure of 50 kPa, l min^{-1}.

It was calculated that air flow rate of VP1 reduced 6.9, 17.8, and 28.1% whereas the reductions were 4.6, 15.8, and 26.4% for VP2 at 50 kPa, respectively at 400, 1,200, and 2,000 m (Fig. 8).



Working vacuum levels of VP1 (kPa)	38	42	46	50
400	-4.7	-5.6	-6.6	-6.9
800	-10.4	-10.1	-11.2	-11.8
1,200	-15.3	-16.0	-17.0	-17.8
1,600	-19.3	-19.8	-22.5	-23.3
2,000	-23.2	-24.3	-26.3	-28.1

Working vacuum levels of VP2 (kPa)	38	42	46	50
400	-3.0	-4.0	-4.8	-4.6
800	-7.0	-8.2	-9.3	-9.6
1,200	-10.9	-13.2	-14.6	-15.8
1,600	-15.2	-17.7	-19.4	-21.0
2,000	-19.1	-21.9	-24.3	-26.4

Figure 8. Air flow rate losses of the vacuum pumps at different altitudes and working pressures.

Fig. 8 explains that when moved from sea level to 400 m, at a pressure setting of 38 kPa, flow rate of VP1 reduced 4.7% whereas the reductions were 5.6 and 6.9% at 42 and 50 kPa, respectively. It was demonstrated that at a given altitude, the increase in the pressure setting reduced the flow rate that can be supplied by the pump. At 2,000 m the air flow rate losses increased up to 23.2, 24.3, and 28.1% at 38, 42, and 50 kPa, respectively. When air flow rate losses were evaluated for VP2, similar trends were obtained to those of VP1, however the changes in the flow rate was not as high as VP1. For instance, during the operation of VP2 at 38 kPa at 400 m, the air flow rate loss was 3.0% whereas the air flow rate loss was 4.7% for VP1 in the same operating conditions. Also, at the highest altitude (2,000 m), the flow rate reduction of VP1 was 26.4% at

50 kPa whereas the loss in flow rate was 28.1% for VP1 under the same conditions. For both VP1 and VP2, whilst the change in air flow delivery was found to be significant ($P < 0.05$) in relation to pump pressure and altitude, the air flow rate capacity based on altitude*pump vacuum interaction was insignificant ($P>0.05$).

Multiple regression equation was obtained for VP1 and VP2 to determine the air flow rate capacities of vacuum pumps as a function of altitude and operating pressure:

$$Q_p = 826 - 0.0482H - 9.67P_p \quad (R^2\text{: } 0.963) \qquad (6)$$

where: Q_p – air flow capacity, l min^{-1}; P_p – operating pressure of the vacuum pump, kPa.

This equation can be used to determine the air flow rate that can be delivered by the vacuum pump at altitudes from sea level to 2,000 m with operating vacuum pressure rage of 38–50 kPa. However, Eq. 6 is only valid for vacuum pumps with air flow rate capacity of 350 l min^{-1}.

Table 4 shows that VP2 can operate one more milking unit compared to VP1 in about half of the cases (eleven out of twenty four), depending on altitude and vacuum pressure setting of the pump. In case of VP2, at vacuum pressure of 42 kPa, six milking units can be operated at sea level whereas only three units can work simultaneously at 2,000 m. When the vacuum setting needs to be higher, for instance 50 kPa, the number of milking units reduce to 4 and 1, respectively at sea level and 2,000 m. The effect of increasing vacuum pressure and altitude was the same on the number of milking units for VP1, too. However, as shown in Table 4, it is not likely to do milking at 50 kPa at 2,000 m using VP1.

Table 4. Maximum number of milking units that can be operated at different altitudes and operating vacuum pressures

Altitude (m)	Vacuum pump 1				Vacuum pump 2			
	Vacuum pressure (kPa)							
	38	42	46	50	38	42	46	50
0	7	6	4	3	7	6	5	4
400	6	5	4	3	7	5	4	4
800	6	4	3	2	6	4	4	2
1,200	5	3	3	2	6	4	3	2
1,600	4	3	2	1	5	3	2	1
2,000	4	2	1	--	4	3	2	1

In this experimental study, it was showed that the changes in altitude and vacuum pressure requirement for a given milking operation had effect on air flow rate capacity of vacuum pump used in practice. Attention should be paid in vacuum pump sizing for a milking machine in that air flow rate losses caused by increased altitude or operating pressure determines the number of milking units to be installed on a milking machine.

CONCLUSIONS

Two vacuum pumps [internal combustion engine operated (VP1) and generator operated (VP2)] used on bucket type milking machines were tested to determine the effect of altitude and pressure setting on the deliverable flow rate.

Maximum pressure of VP1 at sea level was measured to be 94.3 kPa and reduced linearly with increasing altitude resulting in 75.6 kPa a 2,000 m. The corresponding vacuum pressure values were 95.2 kPa and 75.8 kPa for VP2, respectively, which were statistically the same ($P > 0.05$) for both pumps. Maximum vacuum pressure 2,000 m reduced approximately 20% for both machines.

At operating vacuum pressure of 50 kPa, VP1 delivered air flow rates of 336, 287, and 242 l min^{-1} and VP2 delivered 352, 311, and 259 l min^{-1}, respectively at sea level, 1,000 m, and 2,000 m. At 2,000 m, the flow rates reduced 28.1 and 26.4% in VP1 and VP2, respectively. The reduction in the flow rates were greater than the rate of pressure drops (about 20%) at the same altitudes.

VP2 had greater air flow rates compared to VP1, demonstrating that one more milking unit can be operated compared to VP1 in about half of the pressure an altitude settings used in the study.

As a result of this study, it can be recommended that the flow rates of vacuum pumps should be accurately determined at different vacuum pressure and altitudes to determine how many milking units can actually be operated at given conditions. Both the altitude and the pressure setting had an effect on the flow rate reduction. The loss in the pump flow rate should be taken into the consideration when the milking machine is to be sized or selected for a specific application.

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