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Article

Experimental Evaluation of Functional and Energy Performance of Pneumatic Oenological Presses for High Quality White Wines

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Abstract: In this article, experimental tests on two different kinds of pneumatic presses have been carried out in two Apulian wineries to evaluate energy consumption related to yield performance. The presses are employed to process Bombino Nero variety grapes, crushed and transformed in rosé wine though a pomace less process. The pneumatic pressured press realized a 2 h:48 min long process, with a maximum pressure on the product of 1.4 bar and a must moulding of 69% of extracted must. In regard to the vacuum press, the process duration is 3 h:18 min, with a maximum pressure of 0.9 bar and a must moulding of 58%. During the pressing operation, mean values of must flow rate are comparable: 2.1 L min^{-1} m^{-2} for the pressured press and 2.9 L min^{-1} m^{-2} for the vacuum press. However, a more detailed analysis gives more insight on the behaviour of the two presses. In regard to the pressured press, a compression phase characterized by few steps and at lowest pressure values has proven particularly effective, especially in the first phase (must moulding of 41% with a must flow rate of 4.6 L min^{-1} m^{-2}), at the lowest pressure values. On the other hand, by analysing vacuum press process, the phases sequence is much more gradual, must moulding decreases as the extraction proceeds (from 28% to 6%), and in the last three phases a very low amount of must is extracted, with must moulding smaller than 10%. The energy consumption of the pressured press during compression is mainly related to the engine power absorption (one of the two in operation), and it is below 4 kW except during start-up, due to the starting currents. The highest power is reached in the last phase in which the maximum pressure is applied and a great amount of must is extracted. On the other hand, energy consumption in the vacuum press gradually decreases. A similar trend was not observed for the specific energy for either press: while it increases along the whole process for the vacuum press, it reaches a maximum value in the second phase of the pressured one. Results show the need to pursue new studies on single component design and on pressing cycles, especially in high-capacity pneumatic vacuum presses. Several advantages on wine production costs could be achieved, even retaining high quality wines.

Keywords: energetic consumptions; pressured press; vacuum press; pressing programs; must moulding; flows

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1. Introduction

Energetic efficiency is actively pursued at a global level and by the EU because, besides achieving general goals, it allows for a decreased goods price, increased competitiveness and a cutting down of environmental impacts [1]. Several of these benefits should encourage firms to implement energetic efficiency measures, yet this does not often happen.

Energy consumptions are essential for a complete study on a transformation process. In fact, saving energy makes firms more competitive, even keeping high quality products [2]. So, energy can be considered like a raw material to come up with quality products at affordable costs [3,4]. Energy consumption and energy efficiency potential can be evaluated using both mathematical modelling and/or experimental validation [5].

In regard to press performance, most of the studies deal with quality aspects. Generally speaking, interaction with mechanical parts is believed to be one of the most important critical aspects in the production of high-quality wine. There are many technological innovations that can be introduced to reduce the effects of most direct contact with mechanical parts: examples concern the use of particular oenological pumps types (peristaltic, mohno, etc.), remontage systems and, in general, the use of polymeric elastic equipment [6]. The most important technical innovation has probably been the introduction of soft presses that since the 1970s really improved the first production phase. The current availability of pneumatic presses, able to work effectively with pressures at most of 2 bar, could lead one to believe that the evolution of these machines is already completed. This is not true with regard to new geometries, new materials or even new mechanical press models.

Darias-Martin et al. [7] highlighted that design or choice of an oenological press depends on yield and quality needs: maximum production of high quality must, minimum phenols extraction, minimum turbidity and, in many cases, minimum pressing time. Generally, ensuring an adequate must yield is requested in the pressing phase [8]. Pressing destemmed-crushed grape usually takes sensible technical and technological benefits, although it is possible to press whole grapes or employing retracted impeller pumps, as well as a more rapid filling phase. It grants best performances for the press, a faster must transport and reduces the risk of starting unwanted fermentations while the must is within the press [9].

Low pressure values affect the glucane concentration in must extracted from grape pested by Botrytis Cinerea [10]; on the other hand, high pressure allows one to extract more brown-coloured compounds, due to the greater catechins and flavonols content [11]. A comparative study on white wine was carried out by Darias-Martin et al. [7] using two membrane-presses: an open press and a hermetic press; the first one realizes a three-phases pressing cycle, each one repeated thrice, at pressures of 0.5–0.7–1.5 bar, whereas the second press realizes a six-phases pressing cycle, 0.4–0.6–0.8–1.1–1.6 bar, without repetitions but with a 12 h long pre-maceration. Compared to direct pressing, maceration increased the must phenols content, acidity and yield.

Pezzi et al. [6] studied the functional performance of a wide draining surface press with a central tubular membrane, highlighting how geometric and mechanical characteristics influence machine performance, allowing high extraction rates. The machine turned out to be particularly sensitive to working pressure settings and less to the number of pressing cycles and consequently to exhausting time. These characteristics were ascribed to membrane elasticity, uniform distribution of the pomace panel in a limited layer and high specific draining surface.

Two different pressing systems were compared on Sauvignon Blanc by Catania et al. [12], using an innovative closed pneumatic press in two ways: pressing with and without oxygen; the latter led to an increase in total polyphenols and in must total acidity values and sensibly lower 420 nm absorbance. Results are encouraging and open new research perspectives aimed to apply innovative techniques to improve the quality of the finished product.

Mechanical presses are usually considered less delicate for product processing compared to pneumatic presses. Pavloušek [13] asserted that using high pressures is directly related to unwanted compounds, especially solid ones. Consequently, problems in wine fermentation, clarification, filtration or stabilization can occur.

Zemanek et al. [14] compared functional performances of a pneumatic press and a mechanical one processing the same grape variety. Results showed that, with a mechanical press, maximum pressure value was 0.51 MPa for a must moulding between 0.748 and 0.858, depending on variety. For the pneumatic press, maximum pressure was equal to 0.15 MPa, and for the must moulding, it was between 0.803 and 0.865. On the Sauvignon Blanc variety, the mechanical press achieved 268 L/h of must, against 445 L/h obtained with the mechanical press; on the contrary, processing Zweigeltrebe-type grape, characterized by a large and slippery peel, mechanical press performances resulted in a value of 715 L/h, whereas for the pneumatic press, it was about 713 L/h.

In addition, energy lost because of water and alcohol evaporation was also studied by various authors. Williams and Boulton [15] evaluated the effect of several variables, such as inoculation percentage, sugar concentration, must temperature and air temperature in fermenter headspace, on evaporated ethanol rate. Le Roux et al. [16], Lopez and Secanell [17] and Varma [18] developed similar mathematical models, but they always resulted too limited for practical use. Difficulties are due to several factors, such as changes in chemical and physical must characteristics during fermentation. Manzocco et al. [19] studied these properties using a simplified experimental model to simulate a must with 25% sugar producing a 12.78% alcoholic solution, proving big physical and thermal changes. In this study, a fermentation kinetic model was firstly developed that was able to determine must physical and thermal characteristics changes. This model was proved valid in various oenological conditions [20] and it was proposed in a new control system for wine production to optimize tank use and total energy supply. Colombiè et al. [21] developed a mathematical model able to simulate the must thermal needs during the fermentation phase and to indirectly assess the energy required to cool must down. A remarkable regard was held for the tank diameter/height ratio, which strongly affects the global thermal exchange coefficient, especially in forced convention cases. Indeed, with the same volumes, the larger the tank, the higher energy dispersed through sides will be. The thermal model was validated using a 100 L pilot system [21]. Genc et al. [22] realized the energy analysis of a red wine production line and used energy degradation rates to assess the system performances in terms of sustainability. The system thermal efficiency was 57.2% whereas energetic efficiency was 41.8%. The degradation rate of the global total energy increases with the increase in both grape flows and reference temperature.

The results in the scientific literature concern the performance of oenological presses in terms of quantity and quality of extracted must. They were obtained only on specific grape varieties: Albana, Trebbiano, Listan Blanco, Sauvignon Blanc and Zweigeltrebe [6,11,12,14], which are not very common cultivars in the wine production of the Apulian Region (Italy). This article focuses on the purely energy performance of two types of pneumatic presses, in relation to the quantity of obtained must and their pressure working cycles, as they influence the performance of the machines in terms of sustainability and production economy. The qualitative aspects are marginal with respect to the purpose of the study.

Energetic studies in the oenological sector usually concern the heat balance in the fermentation phase and the global production process consumption; no study has been conducted on presses' functional performances in relation to energetic consumption.

In this article, an experimental study was carried out with the main aim of comparing the pressing programs, must moulding, flows and energetic consumptions of two different oenological pneumatic presses used in the processing of same variety destemmed-crushed grapes of typical Apulian viticulture cultivar. This study is useful to evaluate the sustainability and energy aspects of these machines, with the aim of optimizing the extraction process.

2. Experimental Tests

2.1. Experimental Plan

The experimental tests were carried out during the 2020–2021 wine season at Cantine De Falco, Novoli (LE—Italy) and Cantina di Ruvo di Puglia Società Cooperativa Agricola, Ruvo di Puglia (BA—Italy), on a homogeneous lot of Bombino Nero variety grapes, destemmed-crushed to be vinified in absence of pomace to rosé wine. The first winery produces mainly bulk wine sold in tanks; the latter one produces wine bottled in various sizes.

The following pneumatic presses with lateral membrane were tested:

(1) Winery De Falco: open VELO HL 45 open pressured press, capacity of the perforated tank 42.0 hL, perforated tank with 1.5 kW electric engine, diameter of the perforated tank 1.20 m, length of the perforated tank 3.65 m, rectangular grid (2 × 20 mm), side channel compressor with 4.0 kW electric engine, dripping surface of 7.4 m^2, 6.9 m^2 wide food grade rubber membrane, side hatch for whole grapes loading and grape pomace unloading, axial feeding system with pneumatic valve (Figure 1, left);

(2) Winery Ruvo di Puglia Società Cooperativa Agricola: SIPREM VS 360 hermetic vacuum press, capacity of the perforated tank 360 hL, diameter of the perforated tank 1.3 m, length of the perforated tank 8.1 m, orthogonal-trapezoidal grid (2 × 20 mm), perforated tank with 11.0 kW electric engine, electric engine of the vacuum pump 5.5 kW, electric engine of the side channel blower 13.0 kW, nylon membrane with non-toxic food grade coating of 11.6 m^2, dripping surface of 13.6 m^2, rectangular hatch for whole grape loading and grape pomace unloading, axial feeding system with pneumatic valve (Figure 1, right).

Figure 1. Studied presses: pressured press (**left**), vacuum press (**right**).

To evaluate the electric power absorbed by the engines of the machines, a Power quality meter & Analyzer working as a data logger, produced by YOKOGAWA, CW121 model, was used with sampling time of 2 s. This tool allows for the measurement of the energy consumption of single-phase and three-phase loads, considering the possible imbalance of the load in each phase. Measurements have been done by inserting the pliers of the tool in the power line between the electrical panel and the engine of the studied machine.

The acquisition of global energy consumption data was carried out when the draining phase was over and continued during the whole cycle duration. The mass of grapes fed into the press and that underwent the pressing program was calculated (difference between the mass of crushed grapes fed into the press and the must obtained by simple draining), as well as the obtained grape pomace (weighing the mass discharged by the press). The first one was obtained by difference between the mass of grapes that entered the press and the mass of must extracted in the pre-draining phase, whereas the second parameter was determined by weighing the mass of grape pomace unloaded from the press at the end of the pressing cycle.

The press performance was evaluated by measuring the quantity of extracted must and the compression pressure, respectively, with a magnetic level probe inserted in the must storage tank and with gauges installed within the press tank.

Three tests for each studied machine were carried out and a statistical analysis was made using the "Statistics 12.0" (StatSoft Inc., Tulsa, OK, USA); an analysis of variance was realized, and results were compared using the Tukey's multiple range test with a significance level = 0.05.

2.2. Presses Work Cycle

During the two tests, the vacuum press worked with a longer and more gradual cycle because of its capacity seven times bigger than the pressured press. The vacuum press applies on the product pressures up to 0.9 bar; this implies very low-pressure values in the beginning, 0.2 bar, repeated several times in order to extract as much must as possible from the crushed grapes: four repetitions for 0.2 bar phase and three for 0.4 bar phase, for a total duration of 3 h:18 min (Figure 2). During each phase, inflation and deflation alternate, until the maximum pressure is reached, with deflation phases followed by rotations of the internal perforated tank.

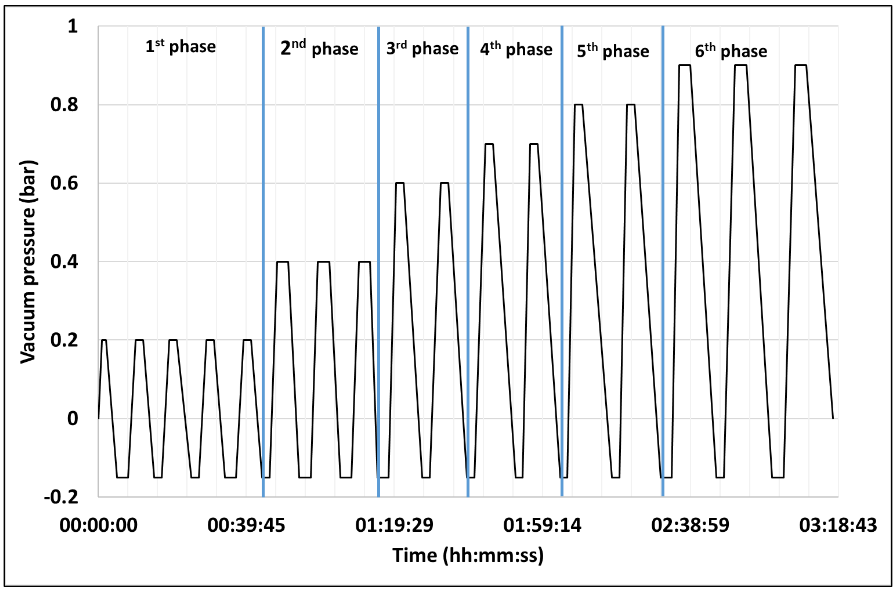


Figure 2. Pressing cycle of the vacuum press.

On the contrary, the pressured press carries out a 2 h:48 min long cycle (Figure 3), that is 30 min shorter, and a program whose pressures range between 0.4 bar and 1.4 bar. In this program, the lowest values, 0.4 bar and 0.6 bar, are repeated only twice, respectively, in the first and the second phase, whereas the highest value is repeated thrice in the third phase.

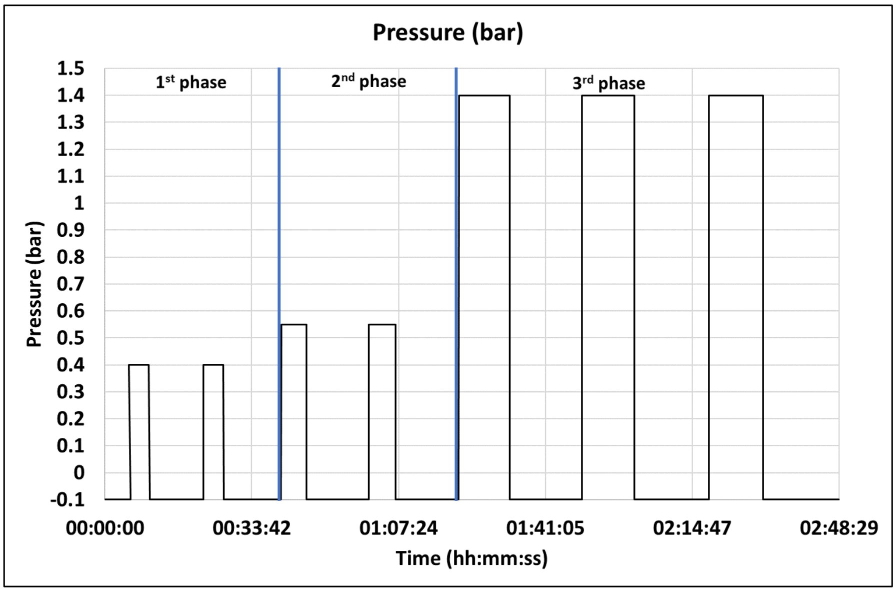


Figure 3. Pressing cycle of the pressured press.

3. Results and Discussion

The results show lower must yield for the vacuum press compared with the other one: 58% and 69%, respectively (Table 1). These values can be misleading as it seems that a greater machine (the vacuum press) has a worse behaviour than the smaller one (pressured press). Analysing the must flow rate through the dripping surface of the perforated tank gives a different point of view. Mean values of must flow rate are comparable: 2.1 L min^{-1} m^{-2} for the pressured press and 2.9 L min^{-1} m^{-2} for the vacuum press. This again seems to contradict the previous result. Therefore, the best way to compare the two machines remains to analyse in detail the whole trend of must flow rate.

Table 1. Functional parameters measured or calculated: mean values along each phase (average values of three measures; all data are significant: $p \leq 0.05$).

Phase	Crushed Grape hL	Must Production hL	Must Moulding %	Phase Duration h:min	Pomace q	Must Flow Rate L min^{-1} m^{-2}
		Pressured		Press		
1	29	12	41	0:40	-	4.6
2	17	3	18	0:40	-	0.9
3	14	5	35	1 h:28	-	0.8
Cycle total	29	20	69	2 h:48	9	-
Cycle average	-	-	-	-	-	2.1
		Vacuum		Press		
1	140	40	28	0:45	-	5.1
2	100	19	19	0:33	-	4.7
3	71	8	11	0:23	-	3.3
4	63	6	9	0:26	-	2.1
5	57	5	8	0:28	-	1.5
6	52	3	6	0:43	-	0.9
Cycle total	140	81	58	3 h:18	59	-
Cycle average	-	-	-	-	-	2.9

In particular, in regard to the pressured press, a compression phase characterized by few steps has proven particularly effective, especially in the first phase (must moulding 41% with must flow rate 4.6 L min^{-1} m^{-2}), at the lowest pressure values, with draining time much longer than maintenance time (Figure 3). A slightly different result is obtained applying the highest pressure (must moulding 35%, due to the reduction in the product to be extracted but with much lower must flow rate 0.8 L min^{-1} m^{-2} due to the longer duration of the last phase) with more repetitions and maintenance time comparable with the draining time. In this way, we have that: at the lowest pressure, must extraction is made easier by long dripping times; at medium pressure, the crushed grape is "prepared" to release later a high percentage of must content. In the last phase, when pressure increases with longer phase duration, the remaining extractable must can be obtained.

An almost constant must flow rate in the second and third phases has to be highlighted.

On the other hand, analysing the vacuum press process, the phase sequence is much more gradual, with draining times always comparable with maintenance ones and much longer low-pressure phases. With this program, a more regular must flow rate is achieved (Table 1). The must moulding is lower and lower as the extraction proceeds (from 28% to 6%) and in the last three phases, a very low amount of must is extracted, with must moulding smaller than 10% (Table 1).

In regard to the must flow rate trend, it gradually reduces from 5.1 L min^{-1} m^{-2} to 0.9 L min^{-1} m^{-2}, remaining always higher than that characterizing the pressured press (Table 1): the pressing cycle is meant to extract the must continuously and regularly. A steady flow of must denotes a low obstruction of the grid; then, cleaning of the vacuum press will be faster and easier, and the machine will be ready sooner to begin a new pressing cycle. This is an advantage that would be more important when processing more "difficult" grapes than the studied ones, with larger and slipperier peels and that are more likely to block the grid. In the latter cases, a pneumatic press would be less effective than a mechanical press, in terms of yield [7,14].

On the other hand, the pressure program depends on grapes, process, and final product. In particular, the vacuum system cannot reach the same pressure values as the compression system, and this explains the differences between the two studied pressure programs. Moreover, in the studied cases, the pressure values could be affected by the need for as much must as possible to ferment later on, due to the firm's production of bulk wine. Anyway, they are still lower than the critical levels for white and rosé wine production [11,23]. Longer times spent by the product in the press may also start fermentation/oxidation processes that are, in most of the cases, undesired [8,24].

Figures 4 and 5 show the trend of the energy consumption during the whole process for the pressured press and for the vacuum press, respectively. In the first case (pressured press), there are only two electric engines, one for the perforated tank rotation and the other for the compressor. Usually, as in the studied case, the pressing program does not include phases in which they work simultaneously. Indeed, the compressor works to inflate or deflate the membrane but always with the electric engine of the perforated tank off. On the other hand, when the compressor is off, the tank rotates, alternatively clockwise and counterclockwise, to break down the pomace panel.

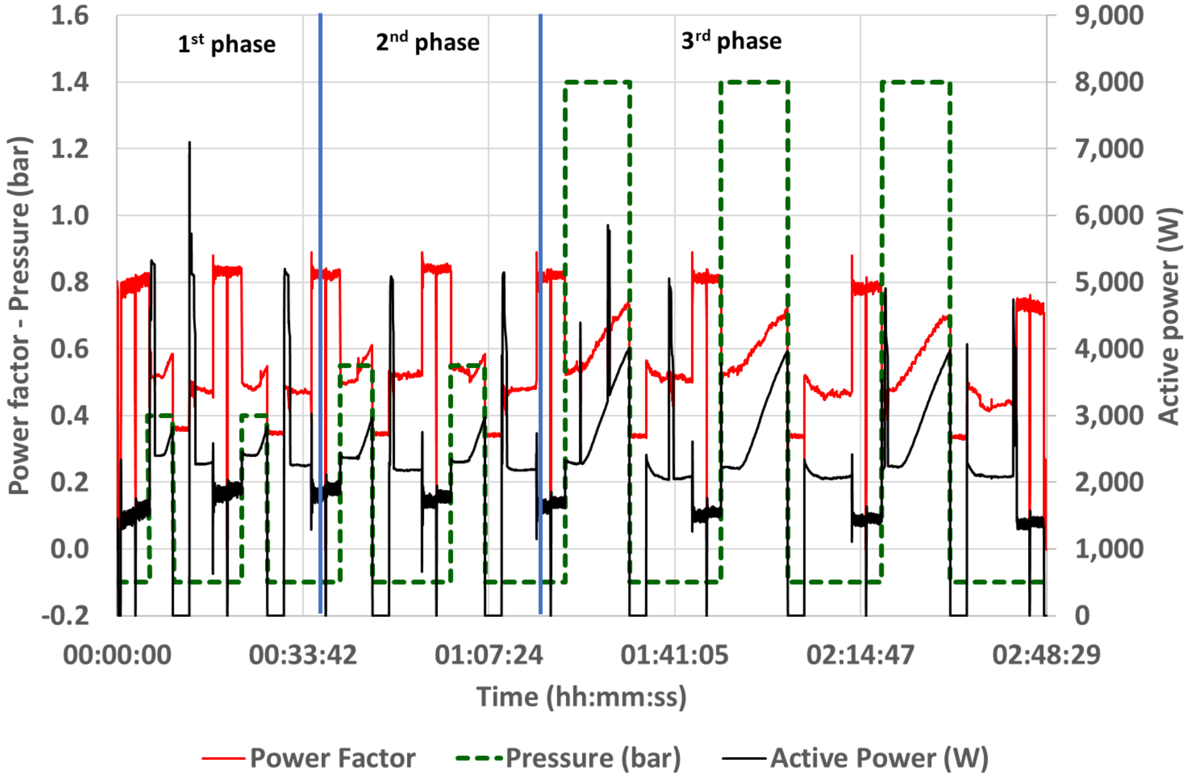
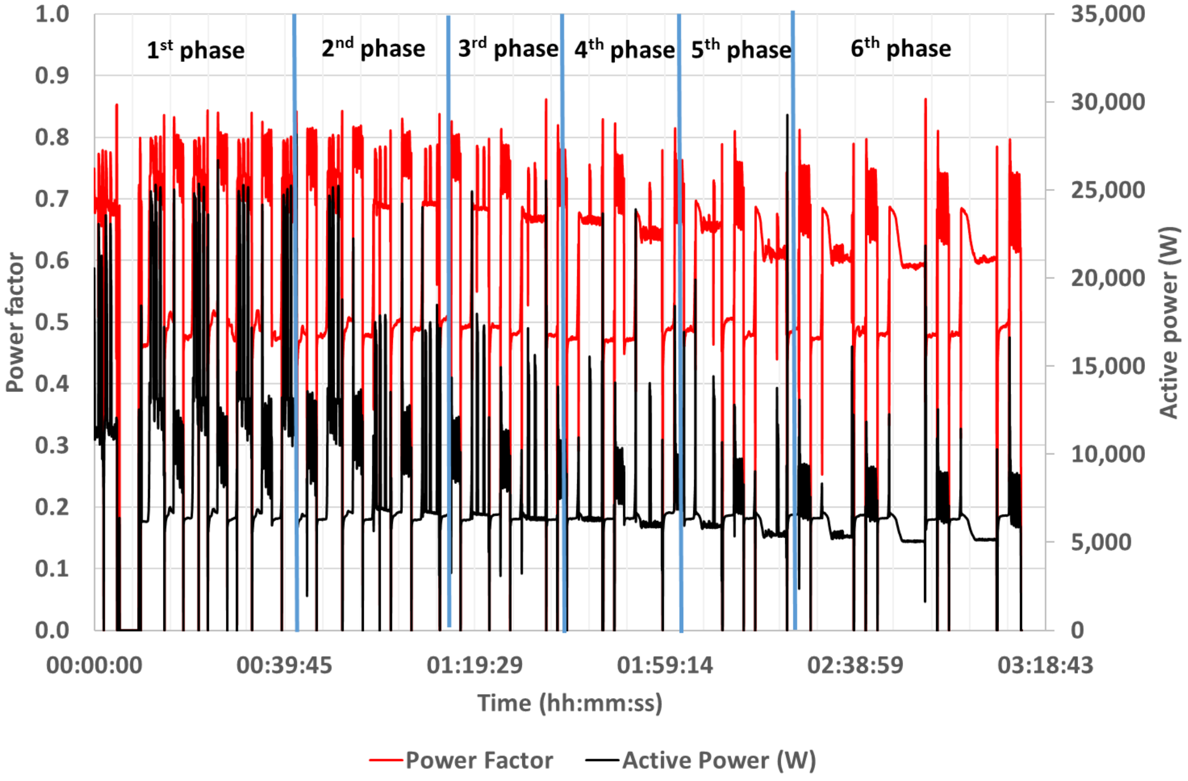


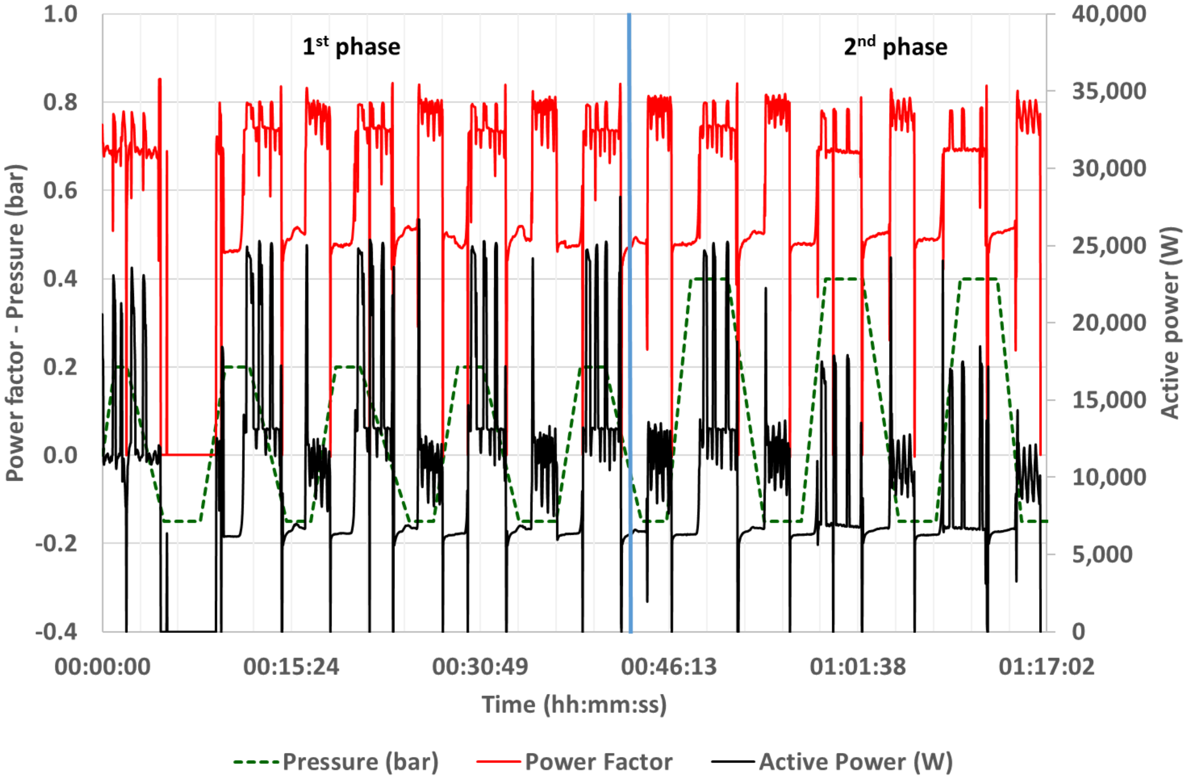
Figure 4. Power factor and active power and throughout the cycle of the pressured press.

Therefore, the energy consumption of the press is due either to one engine or to the other and it is below 4 kW (Table 2; Figure 4), except when due to the starting currents.

The highest power (4 kW) is reached in the last phase of the extraction process (Figure 4), during which the maximum pressure is applied and a great amount of must is extracted from the crushed grapes (Table 1). The absorbed power increases as the pressure applied grows (see the ramps in both trends, active power and power factor, shown in Figure 4). This behaviour depends on the simultaneous presence of two resistances: the first one due to pomace panel compaction and the other one due to the air introduced in the membrane volume.



(**a**)



(**b**)

Figure 5. Power factor, pressure and active power throughout: (**a**) the whole cycle of the vacuum press; (**b**) the first two phases of the cycle of the vacuum press.

Table 2. Energy parameters measured: mean values along each phase (average values of three measures; all data are significant: $p \leq 0.05$).

Phase	Compressor Power kW	Vacuum Pump Power kW	Tank Power kW	Press Power kW	Power/Must W/hL	Power/Crushed Grapes W/hL
			Pressured press			
1	2.8	-	1.8	2.3	191.7	79.3
2	3.0	-	1.9	2.5	833.3	147.0
3	4.0	-	1.5	3.0	600.0	214.2
Cycle average	3.27	-	1.73	2.60	-	-
Total	-	-	-	-	130.0	89.65
			Vacuum press			
1	6.3	0	11.0	8.7	217.5	62.14
2	6.1	0.9	11.2	8.7	457.9	87.0
3	6.6	6.4	9.0	7.8	975.0	109.9
4	6.9	6.1	8.9	7.3	1216.7	115.9
5	6.5	5.3	7.9	6.6	1320.0	115.8
6	6.3	5.0	7.5	6.3	2100.0	121.1
Cycle average	6.45	4.74	9.25	7.57	-	-
Total					93.3	54.0

In regard to power factor, it has acceptable values (0.8) when rotation occurs and the compressor is off, but it becomes too low (0.4–0.5) for most of the time, when the compressor is operating (tank still). This is probably due to design criteria as this machine could also be used for other operations requiring much greater pressure than those used in the studied process.

On the other hand, the energy consumption of the vacuum press tends to gradually decrease after the second phase (Figure 5a: this plot does not show the pressure graph to help readability), as the pressure applied on the product increases (Figure 5b). The analysis is in this case more complex because its components sometimes operate simultaneously.

During all the five cycles of the first phase, the differential pressure of 0.2 bar is obtained using only the side channel compressor. To increase the differential pressure of the membrane on the product over 0.2 bar, a vacuum pump turns on, allowing one to reach higher depression values and a differential pressure on the product up to 0.9 bar.

The pomace panel break down and the must draining are obtained by rotating the tank alternatively clockwise and counterclockwise. This is clear analysing the plot of the active power (in Figure 5b, the plot is zoomed, showing only the two first phases): rotation occurs when active power (and power factor too) oscillates with greater oscillations and when pressure is applied on the crushed grapes (smaller ones during pomace panel relaxation).

Finally, the vacuum press shows a power factor trend better balanced than the pressured press as it is always quite high (0.8 for most time) and decreases to 0.5 when neither tank rotation occurs nor the vacuum pump is operating, that is when only the blower works (both when inflating and deflating the membrane).

Therefore, independently of the machine type (pressured or vacuum) and dimension (small or bigger), the compressor is designed to operate at high pressure values, so it works worst when not in the design conditions.

The analysis on the specific power of the two machines (Table 2) highlights that it gradually increases for the vacuum press. It is increased tenfold (from 217.5 W/hL_{must} to 2100.0 W/hL_{must}) in regard to the active power per unit mass of extracted must and doubled (from 62.14 W/hL_{grape} to 121.1 W/hL_{grape}) in regard to active power per unit mass of processed grapes.

This means that for the vacuum press, the fifth and especially the sixth phase can be considered critical in terms of specific energy consumption, considering that active power per unit mass of extracted must is a more important parameter than active power per unit mass of processed grapes, as the first one represents the energy used to extract the final product. This is due to the low amounts of must extracted. So, the pressing cycle could be improved, for example, by eliminating the last phase or a part of it, increasing both the pomace breakdown and maintenance times of the previous phases.

When working with the pressured press, the specific energy consumption (active power per unit mass of processed grapes) is tripled, increasing from 79.3 W/hL_{grape} to 214.2 W/hL_{grape}. The behaviour of the active power per unit mass of extracted must is different as it reaches its maximum value during the second phase, 833.3 W/hL_{must} (Table 2), as this represents a preparation phase during which a small quantity of must is extracted.

Although energy improvements could be achieved in the vacuum press without significant yield loss, the second phase of the pressured press processing program, being similarly critic, cannot be modified because it is fundamental to prepare the product for the next phase, which is characterized by high yield but also by high energy consumption too (Tables 1 and 2).

4. Conclusions

In this article, the pressing programs, must moulding, flows, and energy consumptions of two different oenological pneumatic presses to evaluate the mechanical and energy aspects of these machines are presented.

In conclusion, studied on the grapes, the pressured press showed better functional performances, in terms of must moulding (69% against 58% of the vacuum one); this result is mainly due to the inflating system and the low capacity, which allow for the application of a pressing program that proved very effective on the used grape variety and is characterized by few phases: the first phase mainly draining and the second phase substantially preparatory to the third one, which occurs at a relatively high pressure for quite a long time.

On the contrary, because of its construction features, the vacuum press realizes a longer program and applies lower and more gradual pressures, and it is very efficient in regard to energy consumption. Indeed, the vacuum press showed a specific consumption per unit mass of extracted must of 130 W/hL and 89.65 W/hL per unit mass of processed grapes. As for the pressured press, the specific consumptions were 93.9 W/hL per unit mass of extracted must and 89.65 W/hL per unit mass of processed grapes.

These results provide useful information both for the selection of the press (type, size, etc.), and for the optimization of the components of the system itself according to the processes to be performed.

Results show the necessity to pursue studies on single component design and on pressing cycles, especially in high-capacity pneumatic vacuum presses. Improvement concerning functional and energy performances can be achieved and several advantages on wine production costs could follow, keeping high quality standards at the same time.

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