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ENERGY RECOVERY IN MINERAL SLURRY PIPELINES

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Abstract. Induction loss systems are used in mining for process control in long-distance pumping, aiming to maintain appropriate pressure levels and control flow. However, these systems dissipate energy, which increases the pumping system's consumption. This work proposes the use of pressure control systems at dissipation points to recover part of this dissipated energy through pumps operating as turbines (PAT), thereby reducing the overall operational cost of the asset. Additionally, PATs allow for continuous control in slurry systems that cannot be controlled by valves due to the material's abrasiveness. An instrumented loop pumping system was developed and constructed to test the proposed system on a reduced scale. As results, it's shown the calibration process, the consequences of the PAT operating with and without a frequency inverter, the performance analysis, the validation of the system, and suggestions for future improvements.

Keywords: Slurry pipeline, energy efficiency, control valve, pipe head loss, pump as turbine, distributed generation

1. INTRODUCTION

In the mining sector, energy efficiency is a significant concern as it consumes approximately 6.9% of the energy used by the industry in Brazil (EPE, 2021). Among the prominent energy consumers, pumps play an essential role in various stages of mining, from material and input transport within the plant to the discharge of production. Improving the efficiency of equipment involved in hydraulic pumping directly impacts ore production costs.

Both the market and academia are seeking solutions to increase this efficiency. Pump manufacturers, for instance, are dedicated to pump improvement.

In this work, we propose the replacement of dissipation systems installed along a pipeline with pressure loss inducers that recover energy. That is, energy production through hydropower while simultaneously aiming to control the pipeline process. Currently, energy dissipation control is primarily achieved using valves for water pumping and orifice plates for slurry pipelines. The proposed control, which involves energy regeneration from the fluid, is performed by turbines coupled to motors that function as generators.

The proposed energy recovery stations in this work should feature slurry pumps mounted in reverse, meaning the fluid enters through the discharge nozzle and is discharged through the suction nozzle. In this configuration, the pump shaft is no longer driven but rather drives a generator controlled by a frequency inverter.

The use of pumps for this purpose is supported by their original field of application. The transportation of mineral slurries through pipelines necessitates equipment that is resistant to abrasion. As the industry for pumps resistant to the

characteristics of mineral slurries is already well-established and extensive, it is advantageous to utilize them in the recovery stations, unlike turbines, which are still relatively unreliable in this application field.

The work described here sought to validate the feasibility of this proposal using a reduced-scale benchtop setup with a closed water loop system. In this way, the behavior of the PAT was evaluated under specific flow conditions.

2. OBJECTIVE

This work aims to present the proposal for continuous control of pressure and flow in slurry pipelines, coupled with energy production through mechanical energy recovery. The feasibility of this control was validated through the characterization of a water pump mounted in a closed-loop system with suitable instrumentation for data acquisition.

3. WHY CONTROL

In the transportation of mineral slurries, the flow in partial section is almost always avoided, where part of the pipe's cross-section contains air and/or vapor instead of product. This is primarily due to the increased average pumping velocity in partial section, resulting in localized pipe wear (which increases exponentially with velocity).

One of the most common occurrences of flow in partial section is the phenomenon known as slack flow. This effect is observed when, at a higher point in the pipe's elevation profile, the fluid's energy level (expressed in meters of fluid column) becomes lower than its vapor pressure. In such cases, the carrier fluid (typically water) begins to boil and form vapor, causing section opening and flow area restriction. Consequences of slack flow include displacement of the pipe's internal lining, collapse of buried pipes, abrupt column closures, and even cavitation.

When the occurrence of this phenomenon is likely (especially at the highest point along the pipe's elevation profile), the designer is compelled to include some orifice stations in the system (a piping arrangement featuring restriction orifices, which can be fixed or switchable). Figure 1 illustrates an example of an orifice station. These stations solely aim to generate pressure loss to ensure higher upstream pressure. Thus, even at lower flow rates, slack flow is prevented. However, oversizing the pumping system is necessary to overcome the resistance of these orifice stations.



Figure 1. Orifices Stations

Figure 2 illustrates the occurrence of the slack flow phenomenon (blue line, approximately at Km 0.5) and the resource used by the designer to prevent this effect, namely the installation of a dissipation station shortly after Km 1.0 with a dissipation of 20 meters. The green line represents the alteration that would be produced in the Hydraulic Grade Line (HGL), which involves an elevation of pressures upstream of the dissipation, including at the high point at Km 0.5, thus preventing the occurrence of negative pressures or vapor formation at that point. The "cost" of this resource is evident in the pump's head for the two cases. Without dissipation, the pump would operate with approximately 36 meters, whereas with the dissipation, this head is increased to about 51 meters, a 42% increase in head and, consequently, in power consumed by the pumps.

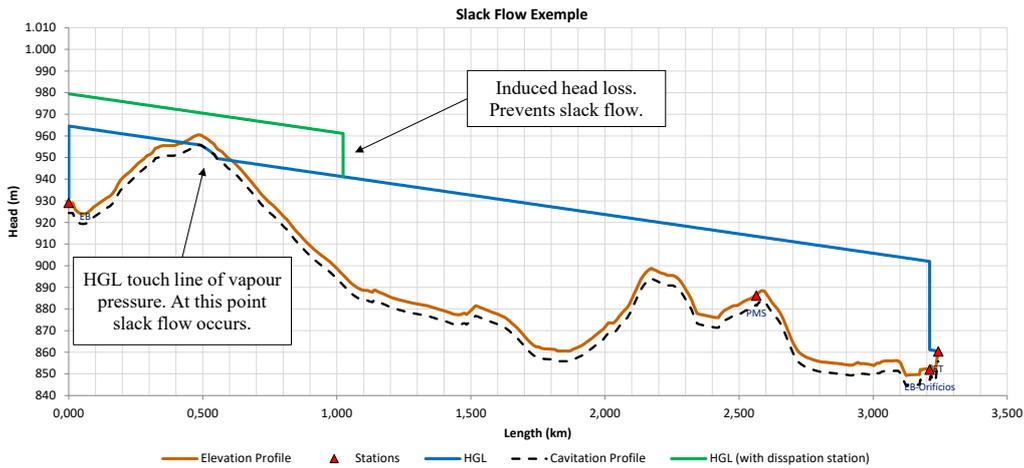


Figure 2. Slackflow Example

4. OPTION FOR RADIAL CENTRIPHIC PUMPS

In order to meet the needs of the mineral industry pipelines (such as Slurry pipelines and Tailings pipelines), the abrasiveness of the mineral slurry becomes a critical factor for the equipment that will be included in the system.

Furthermore, this work does not aim to develop a new equipment for power generation from the pressure drop in the dissipation stations. It is necessary to use a commercially available solution with an established presence in the market that does not require special or exclusive design. Thus, the proposal of the radial pump was chosen, which already has extensive use in pumping systems of various sizes and capacities, such as the Warman line manufactured by the WEIR Group, as illustrated in Figure 3.



Figure 3. Detail of abrasion-resistant internal components of a slurry pump (WEIR Minerals, 2023)

With the equipment operating in reverse, that is, with flow entering through the discharge nozzle and exiting through the suction nozzle, it can be treated as a pump system functioning as a turbine (PFT), as shown in Figure 4. For this case, the literature has already established selection models. Comparing it to turbines (in the case of water pumping), although they have lower efficiency, the cost of PATs makes them economically advantageous.

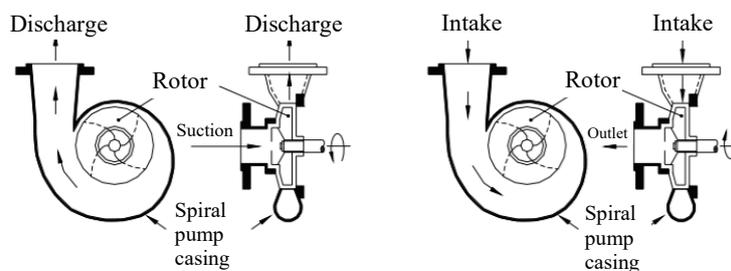


Figure 4. Pump working conventionally and pump working as a turbine (Viana e Nogueira, 1990)

5. EQUIPMENT SELECTION AND BENCH CONSTRUCTION

Appropriate equipment was selected to ensure that the loop test bench is capable of testing multiple conditions and reaching the highest rotations of the PAT.

For this purpose, the system includes a commercial 6.0 hp pump to circulate water at the desired flow rate. To control the flow developed by this pump, the system will have a pressure-sustaining control valve right after the pump discharge. This valve controls the flow by fixing the pump's head at the valve, meaning that changes in rotation directly result in variations in flow, as long as they are within the control limits of the valve.

The loop test bench is also equipped with electronic instrumentation capable of real-time flow and pressure measurements at points of interest. Analog instrumentation has also been included to verify the electronic readings. For system monitoring and control, a supervisory system has been implemented.

The development of the bench relied on the following premises:

- The pumps (pump and PAT) should be of reduced size, considering the available installation space;
- The PAT should be of the radial centrifugal type;
- The arrangement of control valves, flow meters, and pressure gauges should be detachable from the assembly;
- Connections between the pumps, tank, and valve arrangement should be made using flexible piping to improve system mobility;
- The material of the rigid piping should preferably be PVC.

5.1 Main Pump and PAT

The pump for the system was selected to meet cost and space limitations for the project. Therefore, a 6.0 hp centrifugal pump was chosen, capable of delivering a volumetric flow rate of 26,0 m³/h at a head of 36 m.

For the selection of the PAT, once the maximum flow rate and head were known, the Viana Method (Viana, 1990) was used. The method involves estimating the Flow Coefficient (k_q) and Head Coefficient (k_a) which vary according to the specific speed of the pump. Equations 1 and 2 represent these coefficients, respectively. Equation 3 indicates the specific speed of the pump (η_{qA}).

$$k_q = \frac{Q_b}{Q_t} \quad (1)$$

$$k_a = \frac{H_b}{H_t} \quad (2)$$

$$\eta_{qA} = \frac{10^3 n \sqrt{Q}}{(H \cdot g)^{0,75}} \quad (3)$$

Where, Q_b [m³/s]: Volumetric flow rate of the pump; Q_t [m³/s]: Volumetric flow rate of the turbine; H_b [m]: Manometric head of the pump; H_t [m]: Manometric head of the turbine; n : Starting rotation; Q [m³/s]: Pump flow rate; H [m]: Pump head.

According to Viana (1990), the values of the flow coefficient and head coefficient for the desired design point with a starting rotation of 3600 rpm are as follows:

$$k_q = 0,82 ; k_a = 0,71$$

Based on equations 1 and 2, the design point for the pump that will act as the PAT can be obtained. However, this point needs to be corrected for rotation using similarity equations.

A 3 hp 2 pole induction motor PAT has been selected that meets the required system characteristics.

$$Q_{BFT} = 20,7 \text{ m}^3/\text{h}$$

$$H_{BFT} = 24,2 \text{ m}$$

5.2 Arrangement and Assembly

To carry out the assembly, it was necessary to create a simplified engineering flowchart in order to purchase the components. Figure 5 shows the developed flowchart.

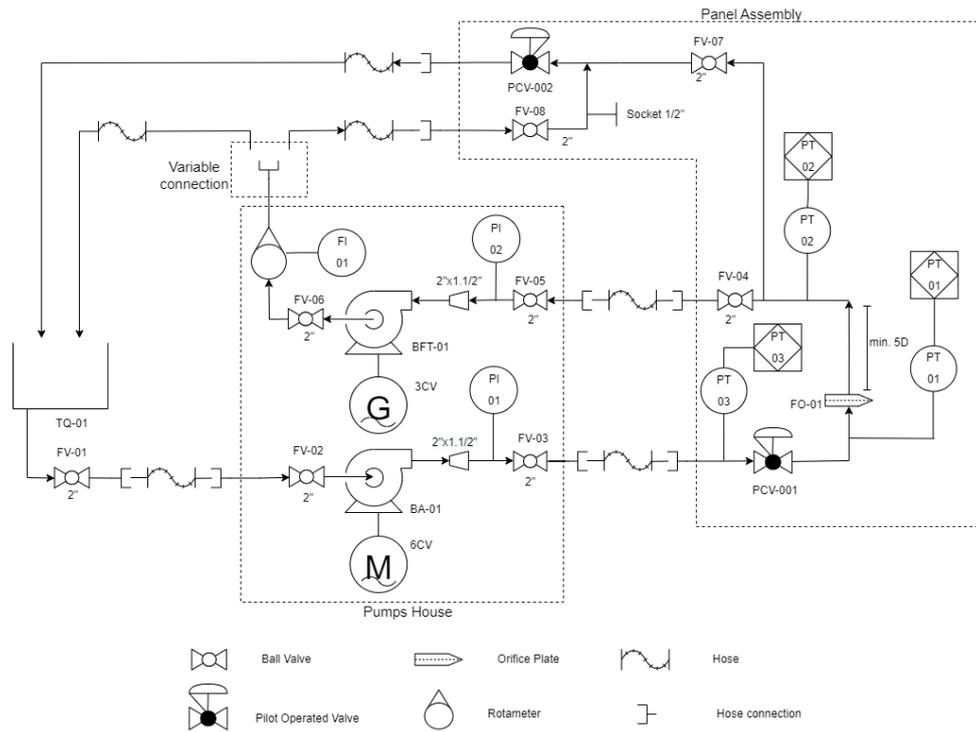


Figure 5. Assembly Engineering Flowchart

Once assembled, the system is highly mobile and modular (as per the assumptions). The complete assembly can be observed in Figure 6.

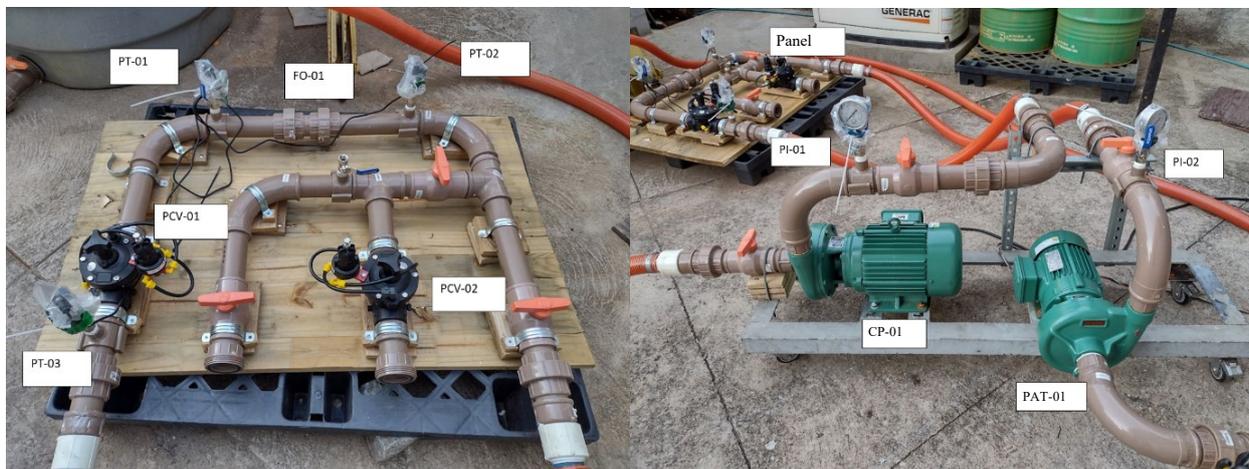


Figure 6. Complete Assembly

5.3 VFDs – Variable Frequency Drive

For the control of both the pump (for flow and pressure control, with the help of a control valve) and the PAT, a solution with two inverters connected through the DC bus was implemented. Since the energy produced by the PAT will always be lower than the energy consumed by the pump in the setup, this arrangement allows the pump to be partially powered by the recovered energy. Therefore, in the setup, there was no need for a regenerative inverter or returning energy to the grid, as energy production only occurs when the loop is operational.

Figure 7 illustrates the assembly diagram of the frequency inverters used.

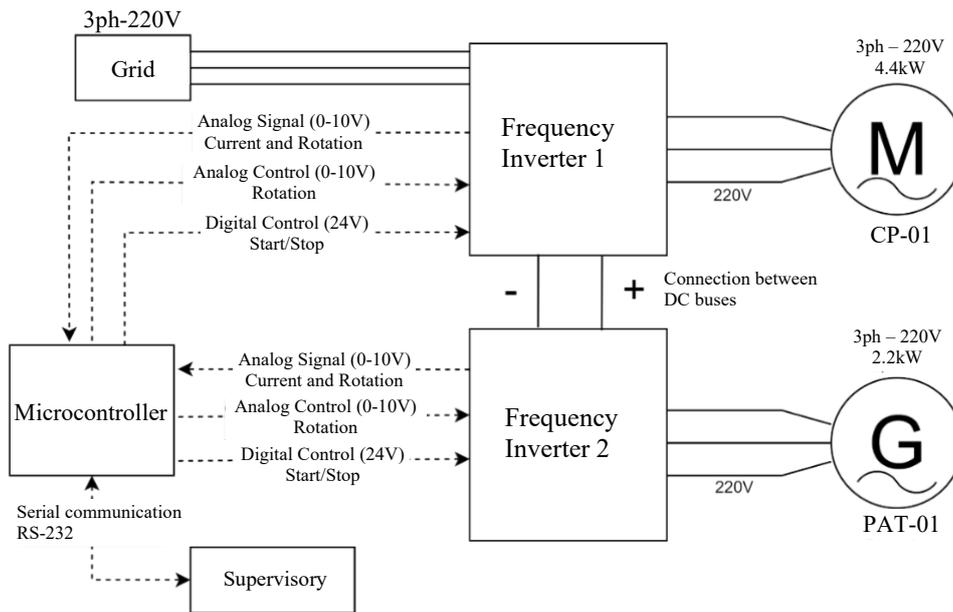


Figure 7. VFD Connection Diagram

5.4 Instrumentation

For the execution of the tests, the installation of instruments in the loop was considered to measure the important process variables for the experiments. The instruments are divided into electronic instruments for digital data acquisition and mechanical instruments for calibration and correction of values. Table 1 presents the instruments and equipment installed in the loop.

Table 1. Instrumentation

Instrument	Nature/Position/Function
PI-01	Downstream pressure gauge of the pump BA-01
PI-02	Upstream pressure gauge of the PAT
PT-01	Pressure transmitter downstream of PCV-001 and upstream of the orifice
PT-02	Pressure transmitter upstream of the PAT and downstream of the orifice
PT-03	Pressure transmitter downstream of the pump BA-01
FO-01	Orifice plate downstream of PCV-001

Subtitle: P = Pressure; F = Flow; I = Indicator; T = Transmissor, O = Orifice

5.4.1 Pressure Measurements

Pressure measurements are taken digitally upstream of the PCV (or downstream of the pump) to control the pump itself, upstream of the orifice plate, and upstream of the PAT (also downstream of the orifice plate) to measure the PAT conditions and flow rate based on the pressure drop across the orifice plate. The discharge pressure from the PAT to the tank is very close to zero, therefore it does not require the installation of instruments.

5.4.2 Flow Measurements

The flow measurements were indirectly performed based on the pressure drop across the orifice plate installed in the loop (between PT-01 and PT-02). Since the measurement is not being taken at the *vena contracta* (0.5D from the orifice plate), a criterion of 5D from the orifice plate will be considered so that the difference between the measurements corresponds to the pressure drop across the plate. Therefore, for water, it can be assumed that the pressure drop is related to the square of the flow rate, as shown in Equation 4.

$$\Delta H = K * Q^2 \quad (4)$$

Where, Q [m^3/s]: Volumetric flow rate; ΔH [m]: Localized pressure drop; K [s^2/m^5]: Pressure drop coefficient.

5.4.3 Current and Rotation Measurements

The current and rotation measurements will be performed using the built-in electronics of the frequency inverters themselves.

5.5 Supervisory

To meet the data acquisition and control requirements of the loop system, a simple supervisory system was developed with the minimum necessary functionalities for data retrieval and recording. The supervisory screen can be viewed in Figure 8.

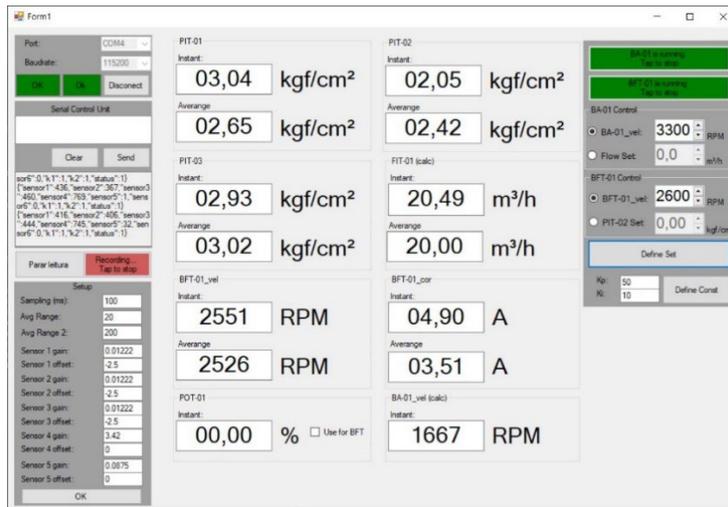


Figure 8. Supervisory Screen

6. RESULTS

The system was built aiming to ensure mobility, and the pumps were mounted on a skid with casters. The control panel was fixed on a wooden base, despite its low resistance to moisture. A conventional 500-liter water tank was used as the reservoir. To facilitate the assembly and disassembly of hoses, threaded unions that can be manually mounted were used as quick couplings. Figure 6 shows the complete assembly and a detail of the control panel.

Before proceeding with the tests, it was necessary to calibrate the test bench by adjusting the flow measurement values with the pressure measurements. Due to a failure in the used rotameter, the pump curve was used as a reference, along with the coefficient of pressure loss (K) of the orifice plate calculated through the analytical method and interpolation of measured values. Figure 9 shows the comparison of the obtained data points with the pump's design curve.

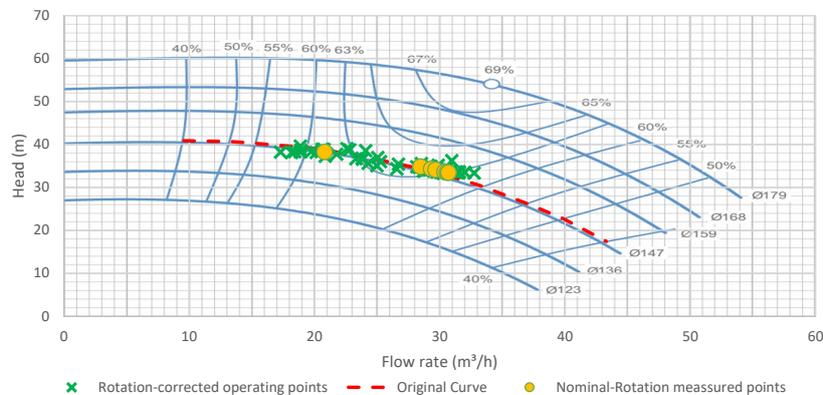


Figure 9. Comparison of the points obtained with the pump curve

The tests were conducted in two phases. Firstly, the PAT was disconnected from the frequency inverter, and tests were performed under this condition. Then, the PAT was coupled to the frequency inverter, and speed variations were

conducted. The first phase is conducted without the PAT coupled to enable the calibration of the instruments, ensuring accurate measurements of flow and pressure.

6.1 PAT Disconnected from Inverter

The graph shown in Figure 10 represents the "no-load curve" obtained when the PAT is disconnected from the frequency inverter. This curve is an important selection tool for the pump. It provides valuable information about the pump's performance under different flow rates and heads when there is no load applied.

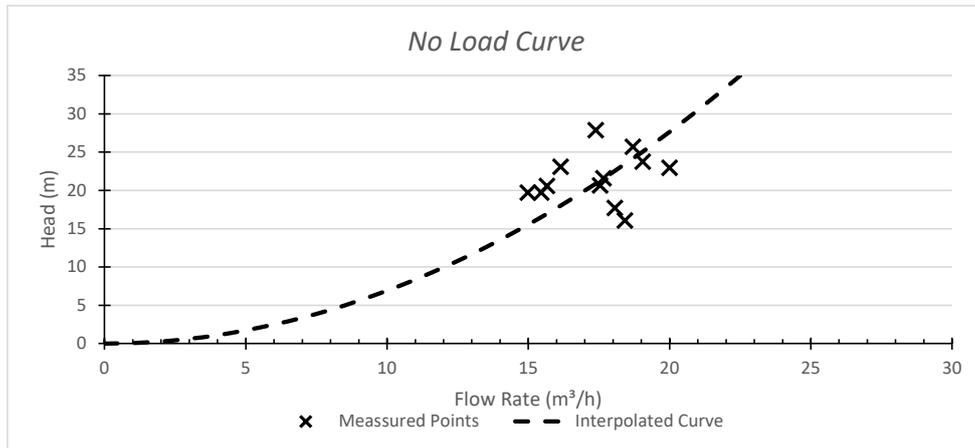


Figure 10. PAT No Load Curve

6.2 PAT Connected to The Inverter

The curves shown in Figure 11 represent the performance of the PAT during the test conducted at a constant rotational speed while it was coupled to the frequency inverter. These curves provide important information about the PAT's behavior under different flow rates and heads.

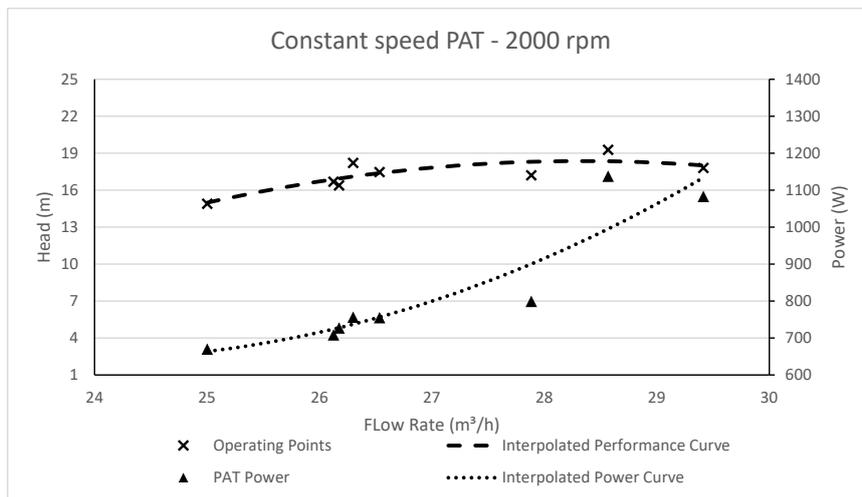


Figure 11. PAT at 2000 RPM – Performance and Power

6.3 Rotation Variation

A PAT start-up test was performed to validate the real-time data acquisition system and analyze the dynamic response of the equipment. The results, including the behavior of pressure, rotation and hydraulic and electrical power, were presented in Figure 12 and Figure 13, along with the efficiency of the complete set and the PAT itself.

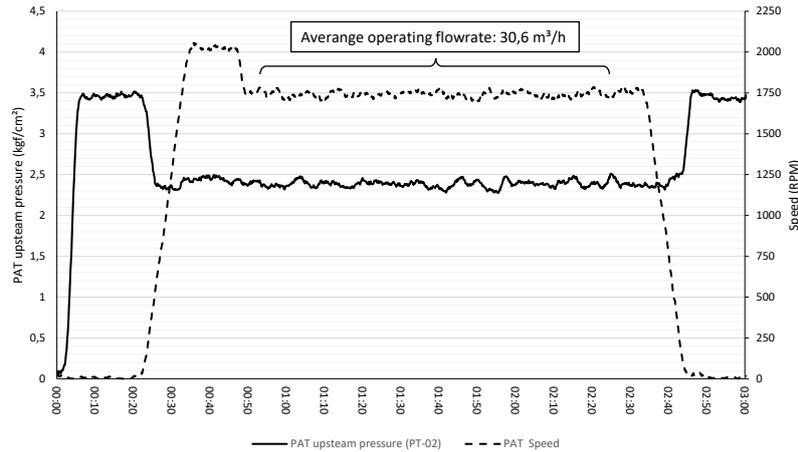


Figure 12. PAT Operation – Rotation and Pressure

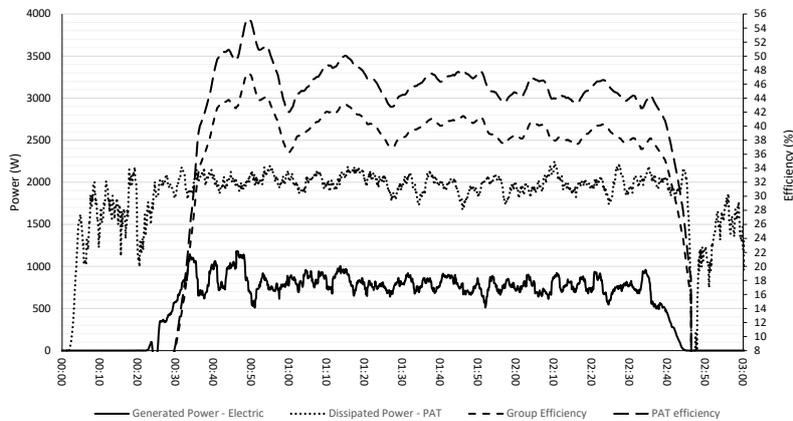


Figure 13. PAT Operation – Power and Efficiency Estimates

It is important to note that when the PAT is not under the control of the inverter, the indicated rotation may be zero, but the PAT continues to move freely. Therefore, it is observed that when the rotation of the PAT is reduced, the upstream pressure also decreases, both when transitioning from 2000 rpm to 1750 rpm and during the starting of the PAT (where the rotation of the free-running PAT is significantly higher than the controlled PAT rotation).

7. CONCLUSIONS

Based on the conducted measurements and tests, several conclusions can be drawn:

- **Calibration:** The digital sensors were calibrated using analog equipment, and due to issues with the rotameter, the flow rate was inferred based on the pump curve predictions. The pressure measurements exhibited some noise, but after calibration, the operating point of the pump could be identified, and the constants for flow rate calculation were calibrated;
- **No-load Operation:** Operating the PAT without control from the frequency inverter, allowing the rotor to rotate freely, resulted in power dissipation due to friction and maximum pressures without flow control. This operation led to high pressures before the brake. When starting the PAT with the frequency inverter at a lower rotation than the natural one, the upstream pressure decreased if flow control was present. In cases of pressure control, there was a significant increase in the system's flow rate. However, if there was no control, both effects would occur, and the system would reach a new equilibrium point;
- **Performance and Pressure Drop:** The obtained results showed good correspondence between the calculated and observed values for efficiency and pressure drop. However, the efficiency values were based on power estimates with uncertainties, highlighting the need for a review of power calculations for the constructed setup;
- **System Validation:** The tests confirmed the functioning of the developed setup, achieving the objective of validating PAT selection models, characterizing their operational behavior, and testing control logic with

PATs controlled by frequency inverters. However, there were identified weaknesses that can be improved in the future, such as installing a more reliable flow measurement system, direct pressure transmitters, and a direct power measurement system for the PAT;

- Future Improvements: The results obtained provided insights for future projects involving PAT application in process control, aiming to implement the proposal in pulp pumping systems. Areas for improvement include a more reliable flow measurement system, direct pressure transmitters, and a direct power measurement system for the PAT.

Overall, the measurements and tests yielded valuable information for future projects and applications of PATs in process control, but further improvements and refinements are necessary to enhance the reliability and accuracy of the setup.

8. ACKNOWLEDGEMENTS

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