Pulsation Characteristics on Volumetric Gear Pump Operation within Hydraulic Circuit

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Abstract: *Hydraulic pumps are essential components in hydraulic systems requiring precise and powerful motion control. The choice of pump depends on factors like the required flow rate, pressure, fluid type, and application environment. Pulsation in the context of hydraulic actuation systems refers to the periodic fluctuation of pressure and fluid flow rate within the hydraulic circuit, often caused by the operation of the pump or other components. Pulsation can have several effects on the performance and reliability of a hydraulic system, and understanding its causes and mitigation strategies is essential.*

Keywords: *Hydraulic actuation, volumetric pump, gear pump, pulsation*

1. Introduction

Within a hydraulic circuit the hydraulic pump is a mechanical device used in hydraulic systems to convert mechanical energy into hydraulic energy. It generates fluid flow, which in turn creates pressure that can be used to power hydraulic machinery and systems.
The common types of hydraulic pumps includegear pumps, with external gear, which is the most common type, using two gears to create flow, it represents simple, durable, and cost-effective solution and internal gear variants, featuring a gear within an internal gear design, often used for high-viscosity fluids.
Other constructive variants of volumetric pumps are represented by vane pumps, namely sliding vane pumps, which use a rotor with extendable vanes able to move within a casing. These variants are efficient and quiet during operation, ideal for moderate pressure applications.
The force units are represented by axial piston pumps, having a certain number of pistons placed in a circular array within a cylinder block. These constructive variants are well known for high efficiency and high-pressure capabilities.
Other piston pumps are the radial piston units, where the pistons are arranged radial around the pump's center, being suitable for very high pressures in operation.
The pump receives mechanical energy from an engine or motor, being able to circulate the hydraulic fluid from a reservoir into the hydraulic system (circuit), which in time provide a continuous circulation with pressure generation. As fluid is moved into the system, pressure is created and together with the volumetric flow rate can be harnessed to do work, such as moving pistons, lifting loads, or powering linear or rotating motors.
The applications that require hydraulic actuation are represented by construction equipment namely in equipment's for excavators, bulldozers, and cranes, industrial machinery used in presses, lifts, and conveyor systems, automotive systems found in power steering, brake systems, and automatic transmissions, aviation industry where is essential for operating aircraft control systems and landing gear.
The key considerations for the volumetric pumps units are represented by volumetric flow rate, which is the fluid volume that pump can move, usually measured in litres per minute (L/min), pressure rate which is the maximum pressure the pump can operate, often given in bar, efficiency value as a parameter that provide the effectiveness of how the pump converts mechanical energy into hydraulic energy and maintenance of the unit, because regular maintenance is required to prevent leaks and ensure longevity in operation.
Positive displacement pumps inherently produce pulsations due to their cyclic nature of fluid displacement. Each cycle of the pump can cause a surge in pressure and flow.

As an undesirable phenomenon in pump operation is registered when a pump's suction side doesn't have enough fluid and can cause the cavitation, leading to irregular flow and pressure spikes.
Although, the cyclic operation related to fluid aspiration and discharge rapid opening or closing valves can create pressure surges and pulsations within the hydraulic system.
Once created and further the lack of proper damping components, such as accumulators or pulsation dampeners, can allow pulsations to propagate through the hydraulic system circuit being possible to reach resonance. Certain system designs can create resonant conditions, amplifying pulsations at specific frequencies.

2. Effects of Pulsation

The continuous operation of the hydraulic circuit with high values of the pulsations provided by the pump leads to the fatigue of the components and the rapid wear of their materials precisely due to the stresses inevitably induced in this way.
Repeated pressure fluctuations can lead to accelerated wear and fatigue of hydraulic components like seals, hoses and fittings [1-7].
Regarding the noise and vibration, pulsations often cause noise and vibration, which can be problematic in environments where quiet operation is necessary.
The hydraulic system pulsations can reduce the efficiency of the working equipment, leading to less precise control and energy losses.
Over time, pulsations can contribute to the breakdown of hydraulic fluid, reducing its effectiveness and leading to imminent contamination.
In this sense, the produced pulsations are stated as total disadvantage and must be reduced at maximum.
In this purpose installing a pulsation dampener can represent a solution to absorb the pressure fluctuations, reducing the severity of pulsations.
Hydraulic accumulators can provide pulsation mitigation solution while these devices are able to store hydraulic energy and release it smoothly, helping to minimize pressure spikes and dips [8-9].
Regarding proper system design, the contribution of the hydraulic circuit design engineer must also be emphasized because a correct dimensioning and adoption of the circuit components so that the disadvantages produced by pressure pulsations are minimized and even avoided.
Regular maintenance of pumps, valves, and other components can prevent issues like cavitation and ensure the system operates smoothly.
Pulsation is a common issue in hydraulic systems, but with proper design, component selection, and maintenance, its effects can be minimized.
Addressing pulsation not only improves system performance but also extends the life of the hydraulic components, ensuring reliable and efficient operation [10-13].

3. Pulsation values for external gear pumps

Pressure pulsations cause vibrations that are transmitted throughout the hydraulic system and affect the components of the drive system in the long term by degrading their material qualities
Reducing pulsation at system pump level is critical for improving the performance, efficiency, and longevity of hydraulic systems.
The external gear volumetric units are particularly used within hydraulic transmission systems for the good mechanical characteristics, high efficiency and low price.
There are also disadvantages which are related to the high noise in operation, the generation of vibrations and pressure pulsations.
The constructive principle of the gear pump is based on a pair of gear wheels that are in gear performing a rotational movement so that the fluid is taken from the low-pressure inlet area through the gaps between the teeth, being circulated in the radial area along pump casing then discharged into the high-pressure discharge area.
The pressure pulsation pattern is thus established between the two low- and high-pressure zones in which the respective volume unit operates [14-17].

An external gear pump is a positive displacement pump commonly used for fluid transfer, wherethe two meshing gears rotate in opposite directions, creating a vacuum that draws fluid into the pump chamber and forces it out under pressure.
The performance of an external gear pump can be described using several equations related to flow rate, torque, and efficiency [18-20].

$$Q = 2 \cdot V \cdot \omega$$

$$V = n_d \cdot V_d \cdot l_l \cdot d_r$$

$$Q_r = Q - Q_l$$

$$N_h = \Delta P \cdot Q_r$$

$$T = \frac{\Delta P \cdot V}{2 \cdot \pi \cdot \eta_m}$$

$$\eta_m = \frac{N_i}{N_h}$$

where:

V-displaced volume per revolution (m³/rev);

ω - rotational velocity (rev/s or rev/min);

Q -theoretical flow rate (m³/s or L/min);

Q_r - realflow rate (m³/s or L/min);

Q_l - flow rate lost due to internal leakage (m³/s);

N_h -hydraulic power (W);

ΔP- pressure rise across the pump unit(Pa);

T - torque (Nm);

η_m - mechanical efficiency of the pump unit;

N_i - input power (W).

The volumetric pumps inherently produce pulsation due to their cyclic nature, but there are several strategies that can be employed in order to minimize the pulsation values during operation.
Pulsation reduction in an external gear pump is crucial for improving the performance, reducing vibration, noise, and enhancing the reliability of the system.
Gear pumps produce pulsating flow due to the nature of their operation, where fluid is moved in discrete volumes between the gear teeth.
A dual or multi-chamber pump design can smooth out the flow by offsetting the timing of fluid delivery between the gears. This design distributes the pulsation peaks more evenly, reducing the overall magnitude of the pressure spikes.
Instead of using standard spur gears, gear pumps with helical or herringbone gear teeth can reduce pulsations. These gears ensure that the meshing occurs more gradually, leading to smoother fluid displacement. The benefits of using helical gears include smoother engagement between the gear teeth, which reduces the suddenness of flow changes and further less abrupt pressure changes, reducing the pulsations intensity.

Fig. 1. External helical gear volumetric unit

Increasing the pump rotational speed while decreasing the displacement per revolution can smooth out flow and this technique reduces the size of the pulses per cycle, leading to a higher frequency but smaller magnitude pulsation, while the smaller individual displacement volumes can create a more continuous flow.
Design improvements in the flow paths of the pump housing, such as optimized intake and discharge ports, can reduce turbulence and pulsations. For example, the tuned port shapes which act for gradually open and close the flow channels minimize sudden changes in fluid velocity.
Incorporating internal baffle help smooth the transitions of fluid flow as the gears engage and disengage continuously.
Implementing torsion dampers in the drive shaft reduces the mechanical vibrations that contribute to pulsation generation. By damping torsion vibrations, the pump operates more smoothly, reducing pressure surges.
Operating two or more gear pumps in parallel, with slightly different timing or phase angles, reduce pulsations and this setup effectively staggers the flow delivery from each pump, ensuring that pulsation peaks do not occur at the same time, leading to a more uniform flow.
Since pulsations often result in noise, focusing on noise reduction techniques like adding noise suppressors or sound-damping materials help reduce the impact of pulsations and these include acoustic enclosures around the pump, or vibration isolation with mounts or pads.
In advanced systems, electronic feedback control systems are used in order to regulate the motor speed or valve positioning dynamically. By adjusting the motor speed, pulsations are mitigated by smoothing the torque applied to the pump unit.
Using flexible hoses or tubing in the discharge line is absorbed some of the energy from pressure surges, helping to smooth out pulsation effects. Soft lines allow for some expansion and contraction, which naturally dampens pulsations [18-19].

4. Numerical analysis on external gear pump pulsation

A numerical approach analysis on pulsation values generated by an external gear volumetric unit involves the simulation and calculation of characteristics related to pressure and flow rate variations in time. This can be achieved by an analytical method based on volumetric unit geometry and operating conditions.
In order to model the pulsation within an external gear unit the following variables are considered:

- Flow rate *(Q)* representing the circulated fluid volume in time unit;
- Pressure *(p)*registered at pump outlet or within the main chambers;
- Rotational velocity (ω) – wheels velocity;
- Fluid volume displaced *(V)*- volume of fluid displaced by the gear teeth per revolution, for which are used the number of teeth, area swept by a single gear tooth, and width of the gear:

$$V = 2 \cdot z \cdot A_d \cdot l$$

Pulsation in the flow can be analyzed by examining the difference between theoretical flow and the actual instantaneous flow due to the discrete nature of gear displacement.
The instantaneous flow rate at any given moment can be modeled as [20-21]:

$$Q(t) = Q \cdot [1 + A \cdot \sin(2 \cdot \pi \cdot f \cdot t)]$$

Where:

A - amplitude of pulsation, representing the extent of flow variation;

f - frequency of pulsation, determined by the gear rotation speed;

t - time.

The number of teeth can be considered as 10, 12 and 14, the rotational velocity of 1500 the frequency values are 250, 300 and 350 Hz.

The pressure pulsation at the outlet can be obtained using a sinusoidal model:

$$p(t) = p + \Delta p \cdot \sin(2 \cdot \pi \cdot f \cdot t)$$

where:

p -mean outlet pressure (Pa);

Δp - amplitude of pressure pulsation (Pa).

f - pulsation frequency (Hz).

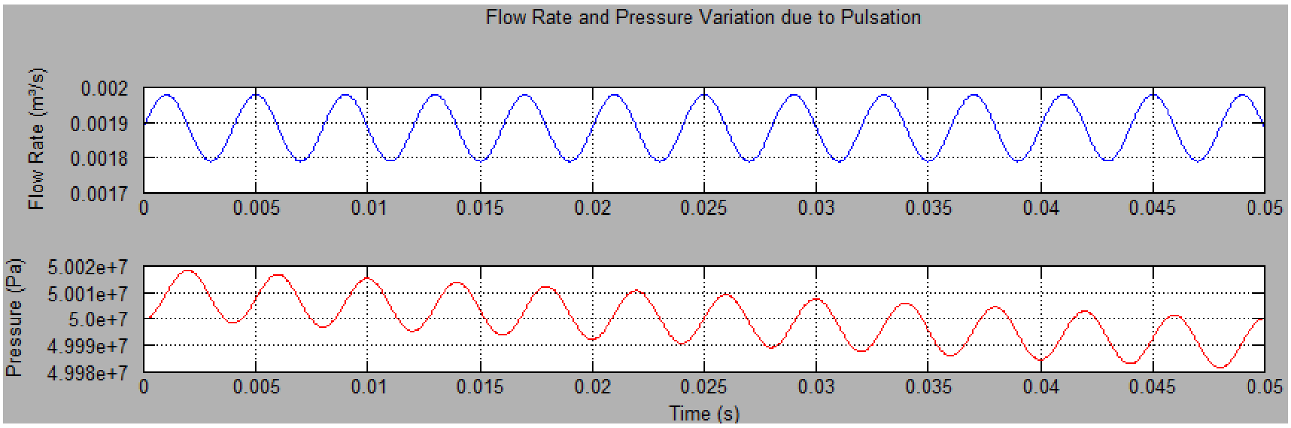
t - time (s).

The amplitude of the pressure pulsation can be determined from the compressibility of the fluid and the flow pulsations, or from empirical data based on the specific pump design.
To numerically analyze the flow and pressure pulsation over time, the time domain must be discretized into small intervals *(Δt)* and compute the flow and pressure for each step.
In table 1 are presented the numerical values used for analysis.

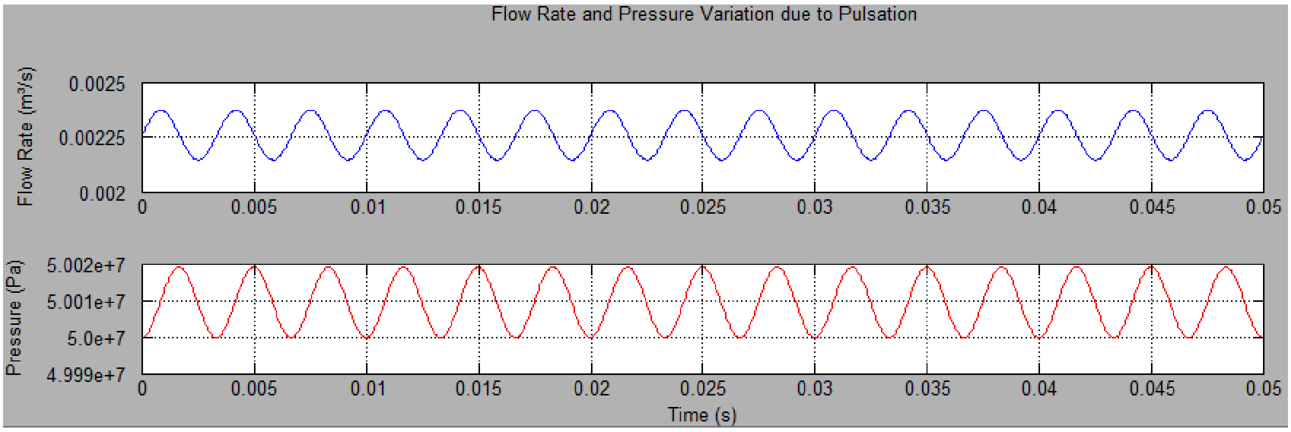
Table 1: Numerical initial values

Crt. No.	Parameter	Value		
1.	Gear diameter	0.05 (m)		
2.	Gear width	0.02 (m)		
3.	Number of teeth	10	12	14
4.	Rotational velocity	1500 (rpm)		
5.	Mean outlet pressure	5 (MPa)		
6.	Pressure pulsation amplitude	0.2 (MPa)		
7.	Pulsation frequency	250 (Hz)		

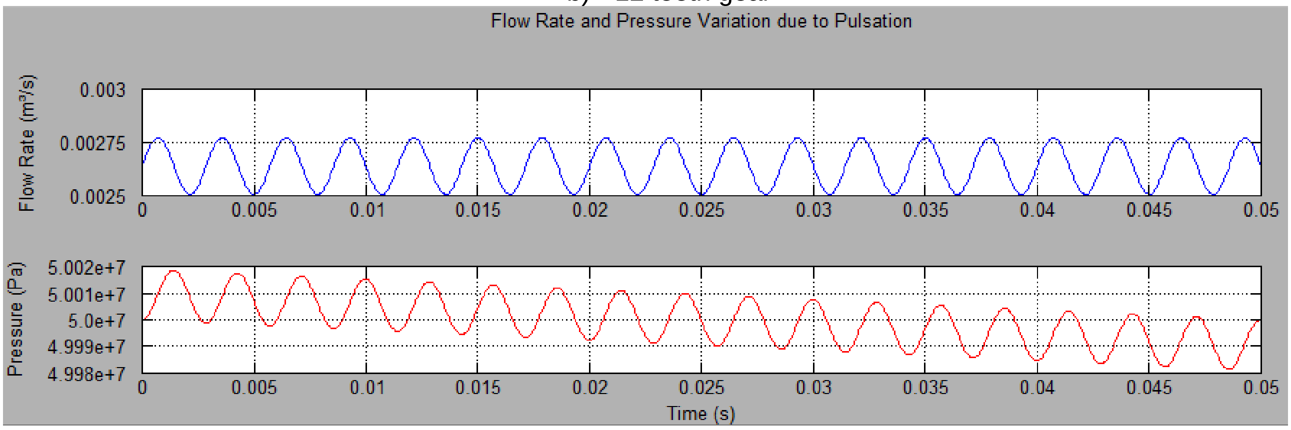
The results obtained are presented in figure 2, being emphasized the fluid flow rate and pressure variations due to generated pulsation in operation of volumetric unit.



a) 10 teeth gear



b) 12 teeth gear



c) 14 teeth gear

Fig. 2. The results for flow rate and pressure due to pulsation according with the number of teeth

The fluid flow rate oscillates around the theoretical value with a 5% amplitude variation due to pulsation, while the pressure fluctuates between 4.9 MPa and 5.0 MPa, corresponding to the mean pressure and pulsation amplitude.
The frequency of the pulsations depends on the rotational speed (RPM) and the number of teeth on the gears and for this case, it will be around 250 Hz.
The obtained results are obtained on a pulsation analysis for the external gear pump, showing how both the flow rate and pressure vary due to pulsations.

5. Conclusions

External gear volumetric units operate by trapping fluid between the rotating gears' teeth and the casing, moving it from the inlet to the outlet. They are positive displacement pumps, meaning that each revolution of the gears displaces a fixed fluid amount and this feature provides a constant theoretical flow rate.
However, due to the discrete nature of the fluid being displaced by individual teeth, pulsations are inevitable. Pulsations are periodic fluctuations in flow rate and pressure, which are linked to the rotational velocity and number of teeth on the gears.
The pulsation frequency in an external gear pump is primarily dictated by the rotational velocity (RPM) and the number of teeth on the gears. In this case, with 10, 12 and 14 teeth and a rotational speed of 1500 RPM, the pulsation frequency is calculated to be in range of 250-350 Hz.
The pulsation frequency corresponds to the frequency at which the pressure and flow rate variations occur as the teeth pass through the pump's high and low-pressure zones and this can be observed as a periodic oscillation in both the flow rate and pressure data.
The flow rate is not perfectly steady and fluctuates around the theoretical value due to pulsation, while the sinusoidal variation in flow rate represents how each tooth displaces fluid intermittently, causing small ripples in the flow.

Although the flow pulsations amplitude is relatively low (5% variation in this case), the pulsations can become significant in high-precision applications or systems sensitive to flow stability.
Similarly, the pressure at the outlet of the pump experiences fluctuations, with a mean pressure of 5 MPa and an oscillation amplitude of 0.2 MPa (±0.2 MPa from the mean). The pressure pulsations follow the same frequency as the flow rate, since they are caused by the same gear tooth interaction.
Pressure pulsations can lead to noise, vibration, wear in hydraulic systems and further if the pulsation frequency resonates with the natural frequency of other components in the system (pipes, valves), it could amplify the effects, causing mechanical stress or failures.
The frequency analysis (FFT) confirms that the dominant pulsation occurs at the calculated frequency, with additional harmonics possibly present depending on the gear geometry and system configuration.
The harmonics represent higher-order pulsations and are typical of mechanical systems where repetitive interactions occur (such as the engagement and disengagement of teeth in gears), contributing to vibration and noise within the system.
While external gear pumps are generally reliable, pulsations can affect the efficiency of fluid delivery, especially in high-precision applications and pulsation dampeners or flow smoothing mechanisms might be necessary in such cases.
Repeated pressure pulsations can lead to fatigue and wear on pump components and connected hydraulic systems. Long-term exposure to pulsation-induced vibrations can reduce the lifespan of the pump and its components.
The gear pump's pulsations, especially at higher frequencies, contribute to acoustic noise and mechanical vibrations, which can be disruptive in sensitive environments or high-performance applications.
While external gear pumps are widely used due to their simplicity and durability, pulsations are an inherent feature that must be managed, especially in applications that require steady flow and low noise. Understanding the pulsation frequency and amplitude allows engineers to design systems with appropriate dampeners or vibration isolation in order to mitigate these effects, ensuring smoother operation and improved pump and system longevity.

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References

[1] Axinti, G., and A.S. Axinti. *Hydraulic and pneumatic drives – Components and systems, Functions and features/Acţionări hidraulice şi pneumatice – Componente și sisteme, Funcții și caracteristici*. Vol. 1. Chişinău, Tehnica-Info Publishing House, 2008.
[2] Axinti, S., and F.D. Șcheaua. *Introduction to industrial hydraulics/Introducere în hidraulica industrială*. Galati, Galati University Press, 2015.
[3] Axinti, G., and A.S. Axinti. *Hydraulic and pneumatic drives – Bases of Calculation, Design, Operation, Reliability and Drive Diagrams/Acţionări hidraulice şi pneumatice – Baze de Calcul, Proiectare, Exploatare, Fiabilitate și Scheme de Acționare*. Vol. 3. Chişinău, Tehnica-Info Publishing House, 2009.
[4] Antoniak, P., andJ. Stryczek.“Visualization study of the flow processes and phenomena in the external gear pump.”*Archives of Civil and Mechanical Engineering* 18 (2018): 1103-1115.
[5]Casoli, P., A. Vacca, and G. Franzoni.“A numerical model for the simulation of external gear pumps.”Paper presented at the 6thJFPS International Symposium on Fluid Power,Tsukuba, Japan, November 7-10, 2005.
[6] Manring, N. D., and S. B. Kasaragadda.“The theoretical flow ripple of an external gear pump.”*Journal of Dynamic Systems, Measurement, and Control* 125, no. 3 (September 2003): 396-404.
[7] Manco, S., and N. Nervegna.“Simulation of an external gear pump and experimental verification.”Paper presented at the JFPS International Symposium on Fluid Power, Tokyo, Japan, March 13-16, 1989.
[8] Del Campo, D., R. Castilla, G. A. Raush, P. J. Gamez Montero,and E. Codina.“Numerical analysis of external gear pumps including cavitation.” *Journal of Fluids Engineering* 134, no. 8 (2012): 081105.

[9] Marinaro, G., E. Frosina,and A. Senatore."A numerical analysis of an innovative flow ripple reduction method for external gear pumps."*Energies* 14, no. 2 (2021): 471.
[10] Rundo, M. "Models for flow rate simulation in gear pumps: A review."*Energies* 10, no. 9 (2017): 1261.
[11] Frosina, E., A. Senatore,and M. Rigosi."Study of a high-pressure external gear pump with a computational fluid dynamic modeling approach."*Energies*10, no. 8 (2017): 1113.
[12] Mitov, A., N. Nikolov, K. Nedelchev,and I. Kralov."CFD Modeling and Experimental Validation of the Flow Processes of an External Gear Pump."*Processes* 12, no. 2 (2024): 261.
[13] Chai, H., G. Yang, G. Wu, G. Bai,and W. Li."Research on flow characteristics of straight line conjugate internal meshing gear pump."*Processes* 8, no. 3 (2020): 269.
[14] Rui, C., L. Huacong, Z. Jiaxing, and G. Ning."Analysis of pressure pulsation in aviation gear pump."*Journal of Physics: Conference Series*1786, no. 1 (2021): 012016.Paper presented at the 11th Asia Conference on Mechanical and Aerospace Engineering ACMAE (2020), Chengdu, China, December 25-27, 2020.
[15] Rabsztyn, D., and K. Klarecki."Experimental tests of pressure pulsation of gear pumps."Paper presented at RESRB 2016: International Conference on Renewable Energy Sources - Research and Business, Wrocław, Poland, June 22-24, 2016.
[16] Sedri, F., A. Riasi, A. Mahdavi Nejad,and H. Metghalchi."Cavitation and Pulsation Reduction for External Gear Pumps Using Novel Core-Feed Inlets and Outlets: An Integrated Experimental and Numerical Study."*Journal of Energy Resources Technology* 146, no. 10 (2024): 102102.
[17] Casari, N., E. Fadiga, M. Pinelli, S. Randi,and A. Suman."Pressure pulsation and cavitation phenomena in a micro-ORC system."*Energies* 12, no. 11 (2019): 2186.
[18] Guo, R., Y. Li, Y. Shi, H. Li, J. Zhao,and D. Gao."Research on identification method of wear degradation of external gear pump based on flow field analysis."*Sensors* 20, no. 14 (2020): 4058.
[19] Corvaglia, A., M. Rundo, S. Bonati, and M. Rigosi."Simulation and experimental activity for the evaluation of the filling capability in external gear pumps."*Fluids* 8, no. 9 (2023): 251.
[20] Xu, B., Q. Liu, Z. Zhu, Y. Gao, C. Li,and Y. Zhang."Influence of the Rotation Speed on the Internal Flow Characteristics of an Aircraft Fuel Gear Pump."*Processes* 12, no. 3 (2024): 576.
[21] Torrent, M., P. J. Gamez-Montero,and E. Codina."Parameterization, modeling, and validation in real conditions of an external gear pump."*Sustainability* 13, no. 6 (2021): 3089.