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A Comprehensive Review on the Design and Performance of High-Speed External Gear Pump for Aerospace Applications

Sameer Ahmed Khan[1], Dr. P Rama Lakshmi[2]
Department of Mechanical Engineering, Chaitanya Bharathi Institute of Technology, Hyderabad, Telangana, India

Abstract- High-speed external gear pumps play a crucial role in aerospace systems, particularly in lubrication, fuel delivery, and hydraulic actuation systems. Their compact size, reliability, and ability to operate at high rotational speeds make them highly suitable for demanding aerospace environments. This paper presents a comprehensive review of the design aspects and performance characteristics of high-speed external gear pumps. The study focuses on key parameters such as gear geometry, material selection, clearance optimization, and operating conditions that significantly affect pump efficiency and durability. Additionally, the impact of leakage losses, cavitation, thermal effects, and fluid properties on performance is discussed. Advanced computational tools such as Computational Fluid Dynamics (CFD) and Finite Element Analysis (FEA) have enabled better understanding of internal flow and structural behavior. Challenges such as noise, vibration, and pressure fluctuations are also addressed. The paper concludes with future research directions including additive manufacturing, smart monitoring systems, and advanced coatings for improved performance.

Keywords— External Gear Pump, Aerospace Applications, High-Speed Pumps, CFD, Efficiency

I. INTRODUCTION

External gear pumps are widely used in aerospace applications due to their simple construction, high reliability, and capability to operate under extreme conditions. These pumps are essential in aircraft engine lubrication systems, where maintaining a consistent flow rate is critical for performance and safety.

The increasing demand for high-speed operation in modern aerospace systems has led to significant research in improving pump efficiency and durability. Earlier studies have highlighted the importance of leakage control, material selection, and gear geometry in determining pump performance.

Recent advancements in simulation techniques and material science have further enhanced the design and optimization of these pumps. However, challenges such as cavitation, thermal stresses, and vibration still persist, especially at high rotational.

1. Working Principle of External Gear Pumps

External gear pumps operate based on the principle of positive displacement. The pump consists of two meshing gears rotating within a casing.

As the gears rotate:

- Fluid is trapped between the gear teeth and casing.
- The fluid is carried from the inlet to the outlet.
- Meshing of gears prevents backflow.

This mechanism ensures a continuous and steady flow, making it suitable for aerospace lubrication systems. The pump consists of two meshing gears rotating within a close-fitting casing. Fluid is drawn into the suction side, trapped between gear teeth and casing, and transported to the discharge side. The meshing of gears prevents backflow and ensures continuous delivery.

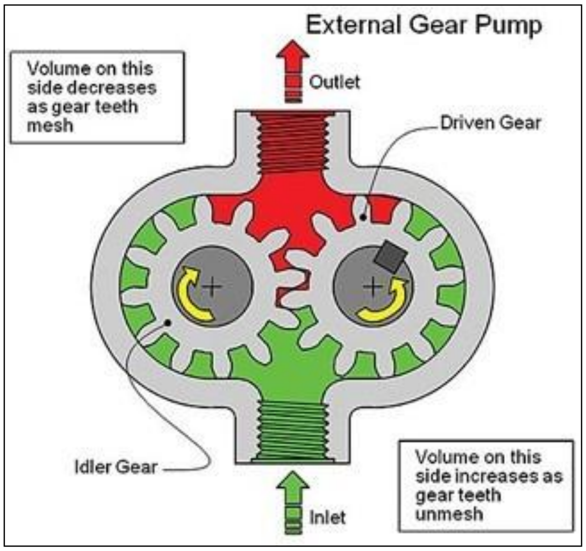


Figure 1: Working Principle of External Gear Pump

2. Design Parameters of High-Speed Gear Pumps

Gear Geometry

The geometry of gears is a primary factor influencing pump performance. Key parameters include:

- Module and number of teeth: Determine displacement and flow rate
- Pressure angle (typically 20°): Affects load distribution and efficiency
- Tooth profile (involute type): Ensures smooth meshing and reduced wear
- Backlash: Must be optimized to balance leakage and friction Gear geometry significantly influences pump performance. Parameters such as module, number of teeth, pressure angle, and tooth profile affect flow rate and efficiency.

Rotational Speed (RPM)

High-speed gear pumps in aerospace applications operate at very high rotational speeds:

- Typical range: 3000 – 20,000 RPM
- Increased speed → higher flow rate
- Excessive speed → cavitation, noise, and wear

Clearances

Clearances between gear teeth and casing play a critical role in leakage control.

- Smaller clearances → Higher efficiency
- Excessively small clearances → Increased friction and wear Clearances directly affect volumetric efficiency:
- Radial clearance (gear tip to casing)
- Axial clearance (gear face to side plate)
- End clearance
- Smaller clearance → higher efficiency but increased friction
- Larger clearance → leakage losses

Pressure and Load Capacity

Operating pressure range: 10–30 MPa (or higher in aerospace)

High pressure increases:

- Mechanical stress on gears.
- Bearing loads.

II. LITERATURE REVIEW

The design and performance of external gear pumps have been widely studied through theoretical, simulation, and experimental approaches. Ivantysyn and Ivantysynova (2001) [1] provided a fundamental understanding of hydrostatic pumps, highlighting the role of gear geometry, clearances, and operating conditions in determining performance. Their work established the basis for analyzing flow characteristics and efficiency in positive displacement machines.

Manring (2003) [2] developed theoretical models to predict flow rate and pressure ripple in gear pumps, emphasizing the influence of gear meshing kinematics. Similarly, Manco and Nervegna (1999) [3] introduced early simulation techniques to study transient pressure variations and trapped volume effects, which are critical for understanding pump reliability and performance.

With advancements in computational methods, Dhar and Vacca (2013) [4] applied CFD-based approaches to analyze internal flow behavior, leakage, and pressure distribution. These models provided improved accuracy compared to classical analytical methods. Castilla et al. (2010) [5] focused on cavitation phenomena, identifying it as a major issue in high-speed pumps that leads to efficiency loss and material damage under low-pressure conditions

Further improvements in simulation techniques were presented by Vacca and Guidetti (2011), who emphasized the importance of integrating experimental validation with numerical models. Pelosi and Ivantysynova (2012) investigated efficiency losses, showing that volumetric and mechanical efficiencies are strongly affected by leakage and friction, especially at high pressures and speeds.

Borghi and Milani (2005) examined leakage mechanisms, highlighting the impact of radial and axial clearances on volumetric losses. Zardin and Vacca (2014) studied flow ripple and noise, concluding that pressure pulsations arise due to periodic volume changes and fluid compressibility. More recently, Kumar et al. (2017) used CFD analysis to evaluate performance under varying conditions, providing detailed insights into pressure distribution, velocity fields, and cavitation zones.

III. MATERIALS AND METHODOLOGY

1. Material Selection

Materials used in aerospace gear pumps must withstand high temperature, pressure, and wear. Common materials include:

- Hardened steel alloys
- Titanium alloys
- Composite materials

Advanced coatings improve wear resistance and reduce friction. Materials must withstand high stress, temperature, and corrosion:

- Alloy steels: High strength and fatigue resistance
- Titanium alloys: Lightweight, corrosion-resistant
- Nickel-based alloys: High-temperature stability
- Surface coatings improve wear resistance and life

2. Operating Conditions

Operating parameters include:

- Rotational speed
- Fluid viscosity
- Temperature
- Pressure

These factors directly affect pump efficiency and lifespan.

IV. RESULTS AND DISCUSSION

1. Performance Characteristics

- Volumetric efficiency depends on leakage losses and clearances. High-speed operation tends to increase leakage, reducing efficiency.
- Mechanical losses occur due to friction between moving components. Proper lubrication and material selection help improve efficiency.
- Overall efficiency is a combination of volumetric and mechanical efficiencies and determines the overall performance of the pump.

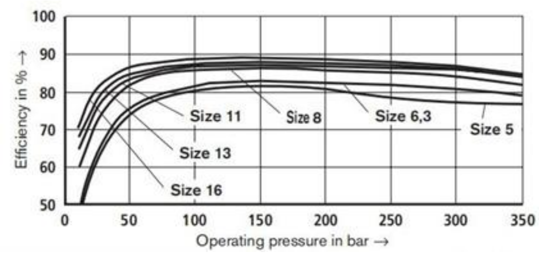
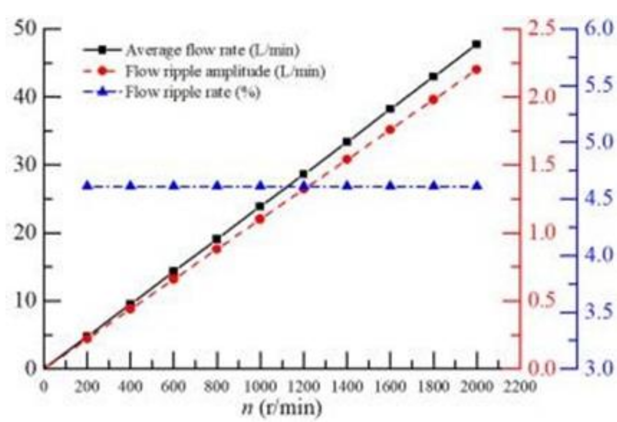


Figure 2: effect of operating pressure on gear pump efficiency

Leakage occurs primarily through tip clearance, side clearance, and journal bearing gaps. These losses become significant at high speeds and pressures, reducing volumetric efficiency.

2. Flow Ripple and Pressure Fluctuation

Flow ripple leads to noise and vibration. It is influenced by gear geometry and rotational speed.



Graph 1: Flow Ripple Variation with Speed

Flow ripple refers to the periodic fluctuation in the discharge flow rate caused by the discrete meshing of gear teeth and the cyclic variation of trapped fluid volumes.

At low speeds, the flow ripple is relatively small and smooth because the fluid has sufficient time to fill the tooth spaces completely, and pressure variations are minimal. The flow output appears more stable, with lower amplitude fluctuations.

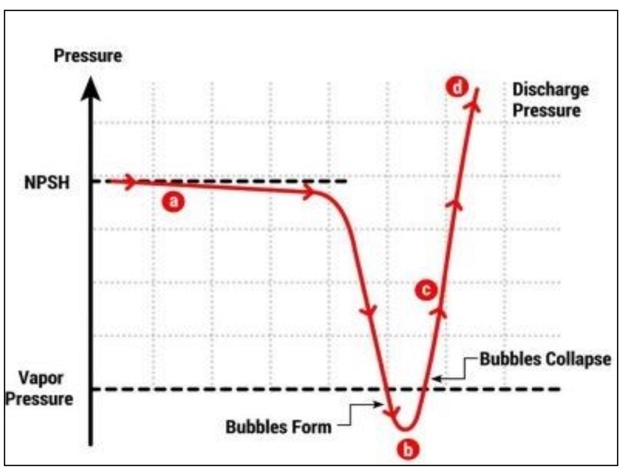
As the rotational speed increases, the frequency of gear meshing also increases, leading to more frequent fluctuations in flow. Although the frequency of ripple increases linearly with speed, the amplitude may either increase or decrease depending on system dynamics.

3. Effects of Cavitation and Thermal Behavior

Cavitation

Cavitation occurs when pressure drops below vapor pressure, leading to bubble formation and collapse. Effects include:

- Noise
- Material damage
- Reduced efficiency



Graph 2: Cavitation

CFD studies show that cavitation in high-speed gear pumps mainly occurs at the inlet and gear meshing zones due to sudden pressure drops. The formation of vapor bubbles reduces effective fluid flow, causing a 5–15% loss in volumetric efficiency. Cavitation also leads to pressure fluctuations, resulting in flow instability and increased ripple.

This negatively affects pump reliability, especially in aerospace applications. Higher rotational speeds intensify cavitation effects. However, improvements such as optimized inlet design, increased suction pressure, and smoother flow paths help reduce cavitation. Proper control of pressure gradients and fluid velocity is essential to minimize cavitation and improve performance.

Combined effect of thermal and cavitation

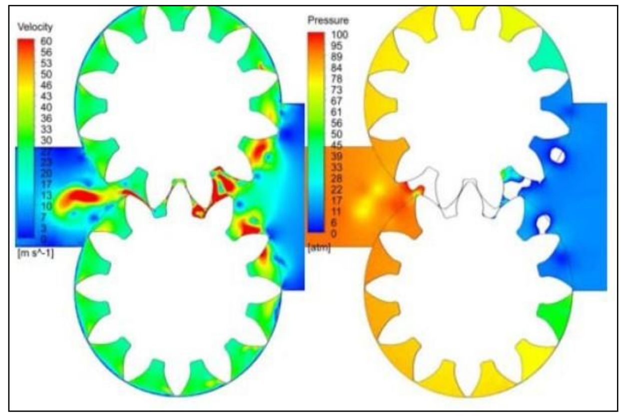


Figure 3: Combined effect of thermal and cavitation

Cavitation intensity in high-speed gear pumps increases with rising temperature due to reduced fluid viscosity and changes in vapor pressure, which promote vapor bubble formation. The combined influence of cavitation and thermal effects can lead to up to a 20% reduction in overall efficiency, along with increased vibration, acoustic noise, and accelerated material degradation.

These factors significantly affect pump performance and durability, especially in aerospace applications. Cavitation and thermal behavior are strongly interdependent and should be analyzed together rather than separately.

In extreme operating conditions, inadequate thermal management can trigger earlier cavitation onset. Therefore, integrated design approaches that combine CFD-based cavitation modeling, thermal analysis, and material optimization are essential to achieve reliable, high-performance gear pump operation.

4. Finite Element Analysis

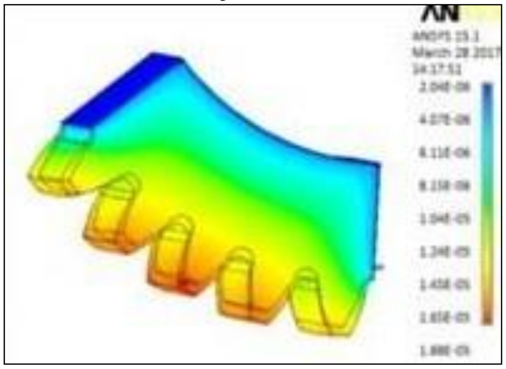


Figure 4: Stresses in gear pump

FEM analysis of high-speed external gear pumps shows that maximum stress concentrations occur at the gear tooth root and contact regions due to cyclic meshing forces, with stresses increasing at higher speeds and pressures.

Thermal analysis indicates uneven temperature distribution, creating thermal stresses and minor deformation at gear tips and shafts. These combined effects significantly influence pump durability. High stress regions may lead to fatigue failure, while thermal expansion alters clearances, increasing leakage.

Therefore, accurate FEM modeling is essential for predicting structural performance. Design improvements, including optimized gear profiles, high-strength materials, and effective cooling systems, are necessary to reduce stress, control deformation, and enhance reliability.

IV. CONCLUSION

High-speed external gear pumps are well-suited for aerospace applications due to their compact design, high reliability, and ability to operate at 3000–20,000 RPM and pressures of 10–30 MPa. However, their performance is significantly influenced by cavitation and thermal effects. Cavitation, occurring in low-pressure regions such as inlet and meshing zones, results in a 5–15% reduction in volumetric efficiency. When combined with thermal effects—such as reduced fluid viscosity and increased vapor pressure—overall efficiency losses can reach up to 20%, along with increased vibration, noise, and material degradation.

Additionally, improper clearances further increase leakage losses, reducing efficiency. FEM analysis shows maximum stress concentration at gear tooth roots, which increases with speed and pressure, potentially leading to fatigue failure.

Thermal expansion also affects deformation and clearances. Therefore, integrated CFD and FEM-based design, along with optimized materials and cooling strategies, is essential to enhance efficiency, durability, and reliability in aerospace gear pump systems.

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