# 博 士 学 位 论 文

# 液氮内喷式主轴组合环形动密封机理与方法

**Mechanism and Method of Combined Annular Dynamic Sealing inside the Spindle with Internal Liquid Nitrogen Spraying**

# 摘　要

以液氮为冷却介质的超低温冷却加工，具有冷却效能高、清洁无污染等优点，对某些难加工材料的切削加工具有显著优势。液氮内喷式主轴是实现超低温冷却加工的重要功能部件，然而液氮极低的温度（-196 ℃）和易汽化的特性常引起结构低温变形和流体低温空化，形成的气液两相流导致动密封物理机理和性能规律被改变，主轴动密封难度很大。本文以液氮内喷式主轴自主研发为目标，开展超低温流体组合环形动密封机理、性能、结构设计等方面的研究工作，并研发出国内首套液氮内喷式机械主轴。

针对主轴内径向空间受限且超低温流体动密封难度大的问题，提出一种节流-阻隔结构串联的超低温流体组合环形动密封方法。依据流体相变过程中气液相热质传递理论，分别建立非接触式宏尺度节流结构的两相流控制方程和接触式微尺度动压阻隔薄膜的两相流雷诺方程，并通过边界条件将两种结构的流场变量相关联，形成组合环形动密封两相流宏-微流场模型，从而揭示不同尺度下两相流流场变量间的数学关系，为超低温流体组合环形动密封机理与性能研究奠定了基础。

为厘清超低温条件下节流结构两相流流场的演变规律，研究了低温变形与空化对节流结构动密封的影响机制。基于热弹性力学相关理论，计算低温和流体压力共同作用下的节流齿热弹性变形；依据常规液相流节流齿隙压降曲线，提出节流结构的流体空化起始判据，最终建立超低温两相流的节流动密封解析模型，并确定模型中的系列经验系数，形成空化前后多相态流场变量的精确计算方法，定量描述了齿隙流体压力、温度、含气率和质量泄漏率的分布规律，为节流密封结构设计提供了理论指导。

为求解接触式唇形结构动密封性能参数，分析了超低温对动压薄膜状态变化的影响规律。基于两相流雷诺方程，辨识出薄膜状态关键变量，通过建立唇口结构低温变形公式与密度随温度变化的关系式，修正考虑低温变形与低温空化的膜厚方程、动压平衡方程和流体能量方程，构建超低温下膜厚、压力、温度和密度之间的关系；设计多层循环迭代的数值计算流程，代入超低温下相互耦合的状态变量并进行求解，获得了两相流动压薄膜的膜厚、压力、温度、含气率、泄漏率等动密封性能参数。

在上述研究工作的基础上，设计了迷宫-唇形串联组合环形动密封结构，提出“逆流向”的超低温流体组合动密封结构优化设计方法，反求计算出面向超低温主轴的高可靠动密封结构参数；基于液氮流体动密封、强化隔热、稳定传输等关键结构，自主研制出最高转速为 6000 r/min 的国内首套液氮内喷式机械主轴，支撑研发出国内首台液氮内喷

式超低温冷却加工机床，并开展了主轴动密封性能综合实验验证，实现了机床结构与液氮内喷式冷却功能的可靠集成。

本文研究工作为发展超低温流体组合环形动密封理论、攻克数控机床重要功能部件研制难题、填补液氮内喷式超低温冷却加工装备国内空白，作出了积极贡献。

**关键词：超低温冷却加工；液氮内喷式主轴；超低温流体动密封；组合环形密封；两相流**

# ABSTRACT

Cryogenic machining using liquid nitrogen as the coolant has advantages of higher cooling efficiency, cleaner without pollution, etc., which has a significant advantage for the processing of some difficult-to-cutting materials. Spindle with internal liquid nitrogen spraying acts as an important functional component for cryogenic machining. However, the dynamic sealing of the spindle is so difficult. The major reason is that cryogenic deformation of sealing structures and cryogenic cavitation of fluid are often caused by the extremely low temperature (-196 ℃) and easy vaporization characteristic of liquid nitrogen, resulting in sealing physical mechanism and performance are changed by the formation of gas-liquid two-phase flow. This paper aims at independent development of spindle with internal liquid nitrogen spraying, and focuses on the mechanism, performance and structure design of combined annular dynamic seal for cryogenic fluid. Eventually, the first domestic mechanical spindle with internal liquid nitrogen spraying is independently developed.

In view of problems that a limited radial space inside the spindle and difficult cryogenic dynamic sealing, a combined annular dynamic sealing method with serial throttle and barrier structures is proposed for cryogenic fluid. According to theories of heat and mass transfer for gas-liquid in process of phase change, governing equations of two-phase flow for noncontact macroscale throttling structure and Reynolds equation of two-phase flow for contact microscale hydrodynamic barriered film are built. Flow field variables of these two structures are correlated through boundary conditions, to form a macro-micro flow field model of two-phase flow for combined annular dynamic seal. Finally, the mathematical relationships among two-phase flow variables at different scales are revealed, to lay a foundation for researches on mechanism and performance of combined annular dynamic seal for cryogenic fluid.

In order to clarify the evolution law of two-phase flow field for throttling structure under cryogenic condition, the influential mechanism of cryogenic deformation and cavitation on throttling dynamic sealing is studied. Based on the theory of thermoelasticity, thermoelastic deformations of throttling teeth due to combined actions of low temperature and fluid pressure are calculated. According to the conventional pressure drop curve of liquid-phase flow inside throttling tooth clearances, a criterion of initial fluid cavitation for the throttling structure is proposed. Analytical models of throttling dynamic seal are established for cryogenic two-phase flow, whose empirical coefficients are determined. Then an accurate calculation method for multiphase flow field variables before and after cavitation is formed. Finally, distributions of pressure, temperature, vapor fraction and mass leakage rate in tooth clearances are described quantitatively, providing a theoretical guidance for structural design of throttling seal.

In order to solve contact lip dynamic sealing performance parameters for cryogenic two-phase flow, the impact of ultra-low temperature on hydrodynamic film state is analyzed. Key variables of film state are identified through Reynolds equation of two-phase flow. Through establishing a formula for cryogenic deformation of lip structure and a relationship between density and temperature, the film thickness equation, dynamic pressure balance equation, and fluid energy equation considering cryogenic deformation and cryogenic cavitation are modified to develop the relationship between film thickness, pressure, temperature, and density at ultra-low temperature. A numerical calculation process along with multi-layer circulation iteration is designed. Finally, dynamic sealing performance parameters including film thickness, pressure, temperature, vapor fraction and leakage rate for two-phase hydrodynamic film are obtained by substituting the above coupling variables under cryogenic condition.

On the basis of the above research work, a labyrinth-lip serial combined annular dynamic sealing structure is designed, and a 'countercurrent' structural optimization design method of the combined dynamic seal for cryogenic fluid is proposed to obtain high reliable sealing structure parameters inside the cryogenic spindle through inverse calculation. Finally, a spindle with internal liquid nitrogen spraying is developed whose maximum speed reaches 6000 r/min based on some key structures including dynamic sealing, insulation and steady transmission of liquid nitrogen, supporting the development of the first cryogenic machine tool with internal liquid nitrogen spraying in China. Comprehensive experimental verifications of dynamic sealing for the spindle are implemented. The results show that a reliable integration of machine structure and internal liquid nitrogen spraying cooling function is realized.

This research makes a positive contribution for developing a combined annular dynamic sealing theory of cryogenic fluid, solving core functional component developing problems of machine tools, and filling the domestic blank of cryogenic machining equipments with internal liquid nitrogen spraying.

**Key Words**: Cryogenic Machining; Spindle with Internal Liquid Nitrogen Spraying; Cryogenic Fluid Dynamic Sealing; Combined Annular Seal; Two-Phase Flow