

# 爆炸0区风机关键技术研究进展及展望

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**摘要:** 油气储运过程普遍存在可燃气与空气混合的爆炸0区环境, 0区风机是保障0区环境安全的重要装置。针对0区风机关键技术, 分类综述了狭小受限空间燃爆规律、流场优化计算、叶轮离心应力与振动、安全轴封技术和阻爆测试领域的研究进展, 并提出了五点展望: ①建立0区风机燃爆测试方法是首要目标, 通过搭建循环回路测试系统来评价抗爆性能; ②在较狭小受限空间, 风机内部旋转结构爆燃转爆轰演化规律存在差异, 应通过实验与计算来揭示; ③分析阻火器对流场的扰动规律, 开展流场优化研究, 以提升风机通气性能; ④研究高转速叶轮应力分布与振动规律, 提出安全应力极限与提升方法; ⑤研发抗爆、导静电耐磨型轴封材料及高效轴封结构。得出以下结论: 通过关键技术研究, 可实现国内0区风机零的突破。

**关键词:** 0区风机; 阻火器; 爆燃转爆轰; 流场优化; 应力; 轴封

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## Research Progresses and Prospect of Key Technologies for Explosive Zone 0 Fans

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**Abstract:** The oil and gas storage and transportation processes were characterized by the explosive 0-zone environment where flammable gas and air were mixed. The zone 0 fan is an important device to ensure the safety of the zone 0 environment. This paper classified and reviewed the research progresses in the fields of narrow confined space combustion and explosion laws, flow field optimization calculation, impeller centrifugal stress and vibration, safety shaft seal technology, and explosion suppression testing for zone 0 fans. Five technical prospects were proposed: 1) establishing an explosion test method for zone 0 fans was the top priority, and a closed-loop test system should be established to evaluate the explosion resistance performance; 2) compared with narrow confined space combustion, the rotating structures within the fan's interior had different DDT laws, which should be revealed through experiments and calculations; 3) analyze the disturbance laws of the flame arrester on the flow field, and conduct a comprehensive flow field optimization study to improve the ventilation performance of the fans; 4) study the distribution and vibration laws of high-speed impeller stress, and propose safe stress limits and improvement methods; 5) develop anti-explosion, anti-static, wear-resistant shaft seal materials and efficient seal structures. The conclusion is that by conducting researches on key technologies, it is possible to achieve a breakthrough in domestically produced zone 0 fans of the same type.

**Key words:** zone 0 fan; flame arrester; deflagration-to-detonation transition (DDT); flow field optimization; stress; seal

## 0 引言

油气储运过程普遍存在可燃气与空气混合工

况, 属于爆炸0区环境, 如 VOCs (volatile organic compounds) 治理系统、低浓度煤层气甲烷富集系统等。VOCs 治理系统全国约 50 万套, 每年处理 VOCs 约 126 万亿  $m^3$ <sup>[1-2]</sup>。VOCs 气体收集和管输是该系统工程的源头, 通常利用风机等动设备进行升压以克服系统管输阻力, 油气回收系统管道

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内部属于连续出现或长期出现爆炸性气体的环境即爆炸0区环境,为燃爆事故的发生提供了重要条件。目前系统中静设备的安全防护已得到充分保障,但对转动设备(风机)的安全防护不足,无法做到0区防爆<sup>[3]</sup>,导致相关事故频发。如2019年山东某石化蓄热氧化焚烧装置回火闪爆,该厂废气风机未设置阻火器,且未采用可防静电材质,风机叶轮高速转动极易形成静电且静电无法导出,达到爆炸极限的预混气遇到静电后发生爆炸。因此,爆炸0区的风机装置整体防爆研究<sup>[4]</sup>至关重要。

本研究对目前0区风机5项关键技术的研究进展进行了综述,为0区防爆风机的研发提供参考依据。

### 1 不同区域风机设计要求

从不同区域风机设计要求(图1)可以看出,爆炸危险级别越高的场所,其应用的风机设备安

全要求愈加严格,0区场所应用的风机应具备电机防爆<sup>[5]</sup>、安全轴封、无火花设计、刚性壳体和阻火功能,并通过风机内部点燃爆炸试验。国外0区防爆风机已发展多年,相关的设计、制造及爆炸测试认证技术已经成熟,但相关核心技术掌握在国外0区防爆风机制造商手中,如德国Fima、英国Halifax和瑞士Meidinger等,技术特点见表1。

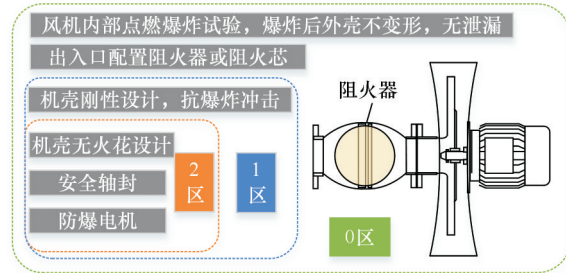


图1 不同区域风机设计要求

Fig.1 Design requirements for wind turbines in different regions

表1 国外0区防爆风机技术特点

Tab.1 Technical characteristics of foreign explosion-proof fans in zone 0

品牌	德国 Fima	英国 Halifax	瑞士 Meidinger
风机图			
技术特点	①风机机壳与阻火器直连,具有最小的爆炸气量;②驱动型式获得防爆认证;皮带、联轴器、直驱;③转子动平衡提高操作安全性;④入口端静态密封,轴封采用涡形迷宫密封;⑤轴承配置温度监控	①轴封采用空气正压破环气体密封;②出入口处安装阻火器,配置火焰捕捉器;③通过联轴器将电机与叶轮连接;④轴承箱配置振动监测	①阻火器配置温度传感器,检测异常工况和介质异常温度;②风机内部耐压设计;③集成火焰控制系统,通过温度传感器监控保证安全;④转速范围大,具有良好的性能范围

目前国内 VOCs 治理系统未有0区防爆风机的应用案例,0区风机研发处于空白。通过技术分解分析,0区风机研究应从风机内部静态和旋转动态可燃气体燃爆规律、设有阻火器的风机动态旋转流场分析优化、叶轮离心应力分析与强度优化、无火花安全轴封研发以及整机爆炸性能测试方法及装置方面开展。

### 2 狭小受限空间气体燃爆规律研究

风机内部设置有旋转叶轮,其燃爆过程属于具有障碍物的气体燃爆类型,且旋转部件带来的气体燃爆规律必定与狭小受限空间(如常规管道燃爆规律<sup>[6-13]</sup>和储罐燃爆规律<sup>[14-17]</sup>)不同。

#### 2.1 管道和储罐气体燃爆规律研究

MALLARD 等<sup>[18]</sup>最早观测到爆燃波到爆轰波的转变现象,证实在气体爆炸过程中存在爆燃和爆轰两种燃烧模式。URTIEW 等<sup>[19]</sup>通过实验研究发现爆燃转爆轰(deflagration-to-detonation

transition, DDT)包含两个阶段,即火焰的逐渐加速阶段和爆轰波的形成阶段。SHORT 等<sup>[20]</sup>研究了非平行通道壁对平面和圆柱形狭窄通道中火焰传播和加速度的影响,对于弱可压缩流动,非平行壁面直接影响压力扩散的速度,显著抑制发散壁面的火焰加速,而收敛壁面的火焰加速得到增强,且圆柱形通道可显著增强火焰加速度。赵永耀<sup>[21]</sup>通过实验发现,甲烷与氧气预混,在初始压力 20 kPa 下,管道长度/直径比达到 37.5 时,a 点位置爆燃转为爆轰,如图 2 所示。

BAUWENS 等<sup>[22]</sup>研究了 64 m<sup>3</sup> 爆炸罐内氢/

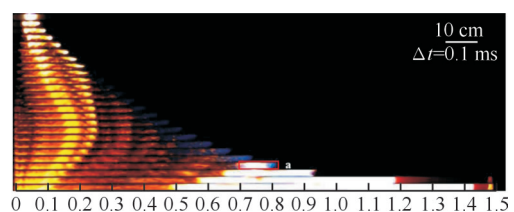


图2 管道内爆燃-爆轰过程<sup>[21]</sup>

Fig.2 DDT process in pipe<sup>[21]</sup>

空气球形火焰加速过程,通过纹影技术捕捉了火焰面的结构,并测量了层流燃烧速率和火焰加速率与火焰半径之间的关系。PHYLAKTOU等<sup>[23]</sup>研究了内径7.6 cm、长1.65 m的封闭圆筒内气体爆炸初期火焰阵面的速度和压力变化规律,发现在总爆炸时间最初的5%~10%火焰速度增加最快且爆炸压力上升速率最大,在此时间段内,火焰传播距离已超过管道总长度的一半。王金贵等<sup>[24]</sup>研究了1 m<sup>3</sup>球形储罐中甲烷-空气预混气的爆炸过程,火焰总体呈规则球形,在热-质扩散因素和流体力学因素的相互促进或制约作用下,火焰总体不稳定性呈现先迅速增强后缓慢减弱的趋势,如图3所示。

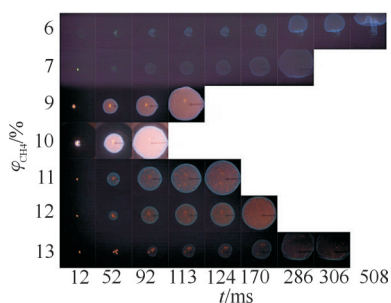


图3 球形储罐预混爆炸过程<sup>[24]</sup>

Fig.3 Spherical tank premix explosion process<sup>[24]</sup>

### 2.2 障碍物对预混气体燃爆规律的影响

对于狭小受限空间内障碍物对气体燃爆规律的影响,很多学者开展了研究。ZHAO等<sup>[25]</sup>研究了非均匀浓度场中不同固体障碍物分布模式对火焰加速(flame acceleration, FA)和DDT过程的影响,发现爆轰起爆过程可分为三种类型:①火焰表面与高压区耦合引起的爆轰;②火焰表面与反射激波相互作用引起的爆轰;③斜激波OS或马赫数MS与流场中障碍物相互作用引起的爆轰,如图4所示。同时障碍物与壁面/障碍物之间形成的空隙中丰富的氢含量和较高的单侧堵塞比都能促进火焰加速,进一步缩短了DDT的上升时间。

WANG等<sup>[26]</sup>研究了不同射流障碍物的布置对火焰加速和DDT过程的影响,发现存在一个能快速触发爆轰的最佳射流障碍物数量。LI等<sup>[27]</sup>研究了含二维圆柱形障碍物通道中氢气-空气混合气的火焰加速和爆燃-爆轰过渡,不同圆柱障碍物排布方式的影响如图5所示,发现火焰加速速率随堵塞比的增大而增大。

HISKEN等<sup>[28]</sup>进行了1.5 m × 0.3 m × 0.3 m(实验室规模)和6 m × 1.2 m × 1.2 m(中型规模)狭小受限空间中丙烷-空气气体爆炸实验,对几种障碍物配置进行了测试,研究其对火焰加速

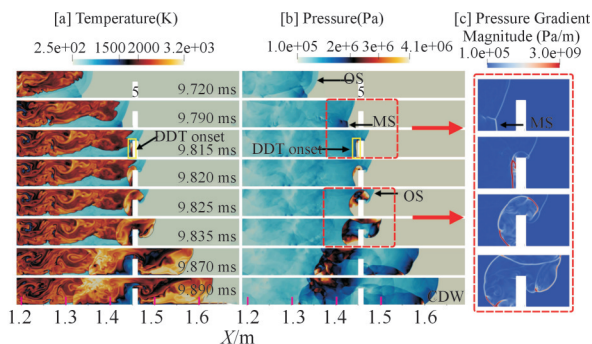


图4 矩形障碍物对火焰加速(FA)和爆燃到爆轰(DDT)过程的影响<sup>[25]</sup>

Fig.4 Effects of rectangular obstacles on FA and DDT processes<sup>[25]</sup>

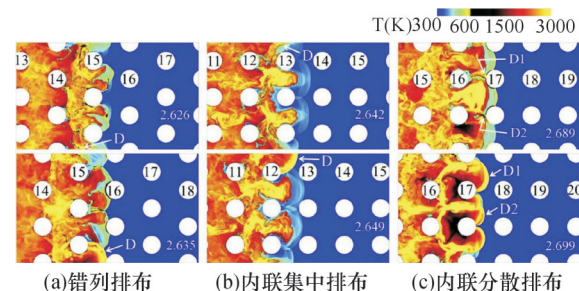


图5 圆柱形障碍物对火焰传播的影响<sup>[27]</sup>

Fig.5 Effect of cylindrical obstacles on flame propagation<sup>[27]</sup>

度和最大爆炸超压的影响。HAN等<sup>[29]</sup>研究了障碍物位置和氢气体积分数的耦合效应对火焰加速和密闭管道内超压变化的影响,如图6所示,发现障碍物向后移动对火焰加速度的影响并不总是单调的,会同时影响最大火焰速度和最大超压。

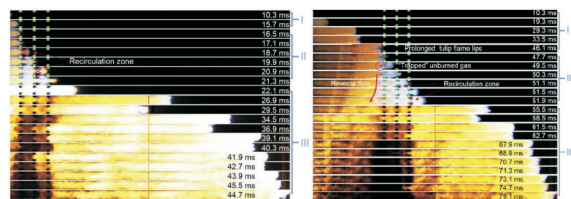


图6 不同障碍物位置对火焰传播的影响<sup>[29]</sup>

Fig.6 Influence of different obstacle positions on flame propagation<sup>[29]</sup>

### 2.3 壁面粗糙度和曲率对预混气体燃爆规律的影响

由于风机叶轮是金属制品,必然存在一定的壁面粗糙度和曲率,此类影响因素对预混气体燃爆规律的作用机制研究已有报道。

ZHANG等<sup>[30]</sup>解释了火焰蔓延的加速和角度对火焰传热的影响,涡流的变化导致了火焰的附着现象,火焰附着长度随角度的增加而增加。ZHAO等<sup>[31]</sup>研究了壁面粗糙度对充满氢-空气混合物的狭窄通道内火焰加速、爆燃-爆轰过渡和爆

轰传播的影响,结果表明:粗糙度增强了边界层的作用,促进了火焰加速FA和爆燃-爆轰过渡DDT的产生,如图7所示。在粗糙度较大( $Ra > 0.1 \mu\text{m}$ )的通道中,腔状区域会产生漩涡、剪切甚至湍流,引发爆轰。

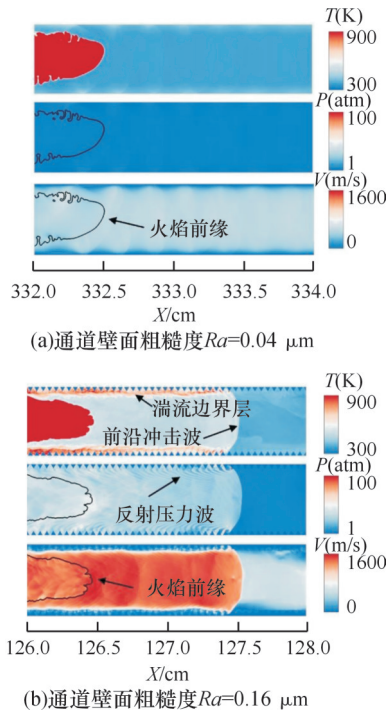


图7 壁面粗糙度对火焰不稳定性的影响规律<sup>[31]</sup>

Fig.7 Effect of wall roughness on flame instability<sup>[31]</sup>

LI等<sup>[32-33]</sup>研究了微通道中预混火焰的曲率通道和螺旋通道对火焰传播的影响,发现螺旋通道内的火焰演化与直线通道内的火焰演化有显著差异,在火焰加速阶段,火焰的传播速度在螺旋通道中呈指数增长,如图8所示,而在直线通道中呈线性增长,原因是螺旋通道中存在很强的横向速度梯度,与直通道相比,螺旋通道可以大大加速火焰,缩短DDT的距离。

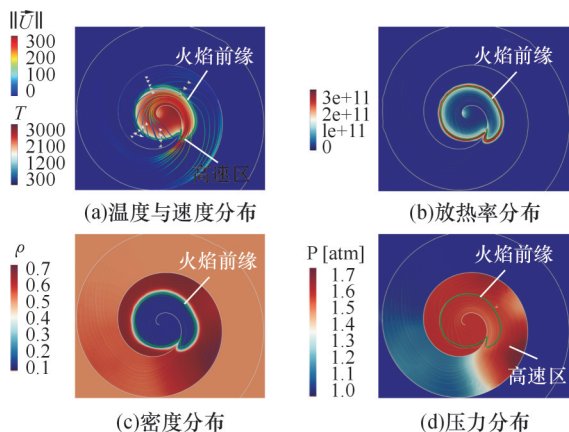


图8 螺旋通道气体燃爆火焰传播变化<sup>[33]</sup>

Fig.8 Spiral channel gas explosion flame propagation changes<sup>[33]</sup>

小结如下:风机内部动态与静态的燃爆规律是0区防爆风机研发的基础数据,可用于指导0区风机外壳抗爆压力设计、轴封材料安全抗爆性能参数确定等工作。然而,国内外主要针对平行壁面、圆柱形通道、储罐和曲率通道开展了气体燃爆火焰传播规律研究,叶轮通常由扭转、扫掠、倾斜三维参数设计确定,针对风机中复杂叶轮结构的气体燃爆演化规律研究还处于空白,关于叶轮腔体结构内气体燃爆火焰传播与旋转流场相互作用的规律有待揭示。

### 3 风机流场优化计算研究

0区风机与其他类型风机不同,其出入口需设置阻火器保障阻火安全。阻火器的波纹板式结构必然引起0区风机流场的扰动<sup>[34]</sup>,因此,针对风机动态旋转流场的优化工作亦是关键,优化的要素包括风机蜗壳、叶轮叶片及组合结构。

#### 3.1 蜗壳对风机升压性能的影响

蜗壳主要用于收集叶轮中甩出的气体,形成风压,其出口扩压器一般做成向叶轮一边扩大、蜗壳出口处有舌状结构,一般被称为蜗舌。蜗壳作为风机的外壳,其外形对流动的影响引起学者们的关注<sup>[35-38]</sup>。

BALONI等<sup>[39]</sup>对单级离心鼓风机蜗壳内三维流动进行数值模拟和矩阵实验,在1.5倍叶轮宽度、 $24^\circ$ 舌角、蜗壳外径减小10%的情况下,压头和流动均匀性较其他情况有所提高,优化后效率提高7.4%。NILUGAL等<sup>[40]</sup>研究了蜗壳倒角对前掠式离心风机性能的影响,发现倒角比为4.4的配置可使静压上升系数提高约6.3%,总压力系数提高约3%。SHEN等<sup>[41]</sup>在蜗壳上设计了一种新颖的纵向沟槽结构,与原蜗壳相比流动面积增加了5%,如图9所示。

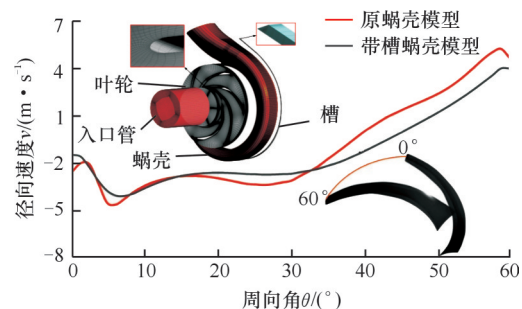


图9 纵向沟槽结构对流动面积提升的影响<sup>[41]</sup>

Fig.9 Influence of longitudinal trench structure on flow area enhancement<sup>[41]</sup>

ASOMANI等<sup>[42]</sup>研究发现,泵-水轮机模式运行时的不稳定性主要取决于叶轮-蜗壳相互作用

在流道内产生的压力和速度波动强度,通过对蜗壳关键几何参数和计算设计方法优化的改进,降低了泵在运行过程中的水力损失。HARIHARAN等<sup>[43]</sup>对四种不同宽度比的平行壁蜗壳和矩形蜗壳的性能进行了研究,发现平行壁蜗壳具有更高的静压恢复和更低的损耗,平行壁面蜗壳在蜗壳进口处的静压分布更为均匀,采用平行壁蜗壳可使离心鼓风机的整体性能提高6%,如图10所示。

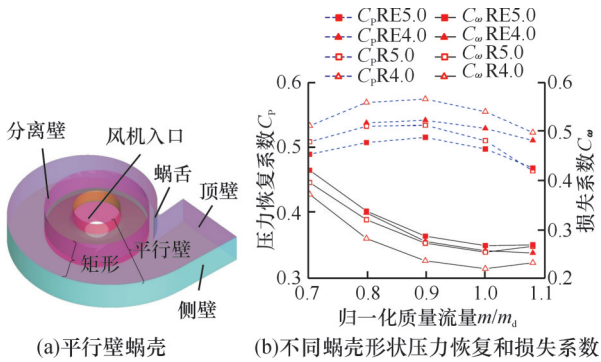


图10 平行壁蜗壳优化性能提升<sup>[43]</sup>  
 Fig.10 Performance improvement of parallel wall volute optimization<sup>[43]</sup>

### 3.2 叶轮对风机升压性能的影响

离心风机叶轮的叶片形状有单板型、圆弧型和机翼型<sup>[44-52]</sup>等类型。不同的叶片形状引起风机的流动特性亦不同。

AYDIN等<sup>[53]</sup>基于ANSYS/响应面优化工具对叶片进行了叶片角、壁厚和长度等参数的优化,优化后,改进型混流风机的最大轴功率降低了8.62%,最佳工作点总压值提高了8.70%,混流风机的效率提高了16.42%。LEE等<sup>[54]</sup>设计了一种三维、光滑、弯曲的叶片,叶片前缘的流动分离明显减少,如图11所示,风机通道内的静压得到了均匀稳定的增加,与原模型相比,静态效率提高了6.3%。

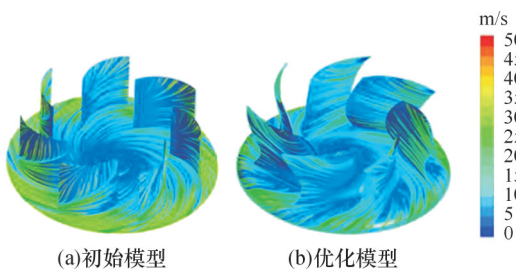


图11 初始模型与优化模型风机叶轮速度流线<sup>[54]</sup>  
 Fig.11 Original model and optimized model wind turbine blade velocity streamlines<sup>[54]</sup>

SAFARI等<sup>[55]</sup>研究了分流叶片、回传通道宽度比和壁面发散角的影响,结果表明:增大宽度比

可以提高节流区附近的效率和压比,采用分流叶片可使均压比和多向效率分别提高0.74%和3.21%。ZHOU等<sup>[56]</sup>采用改进的Hicks-Henne函数对多叶片离心风机叶片进行参数化设计,在最大效率点,优化后风机的流量增加了1.18 m<sup>3</sup>/min,总压效率提高了4.21%。LEE等<sup>[57]</sup>研究了叶片形状变化对进口和出口压力、流量、扭矩和离心风机功率的影响,发现在所研究的4种不同叶轮中,前曲风扇肋型的性能最好,最大流量为2.2 m<sup>3</sup>/min。LIU等<sup>[58]</sup>从能量泄漏的角度分析了叶尖间隙和偏心距对风机气动性能的影响,结果表明:过大的叶顶间隙会使风机效率显著下降,且效率变化梯度较大;同理,随着偏心距的增大,效率也随之降低。ZHANG等<sup>[59]</sup>研究了叶片型线在不同速度分布函数下离心风机性能的影响,结果表明:相比初始叶型,基于速度分布方法设计的叶型叶轮在蜗壳舌附近的旋涡较小,通道内远离蜗壳舌的流场更稳定,流动分离得到有效抑制,如图12所示,具有三段减速功能的叶型在四种设计模型中综合性能最高。

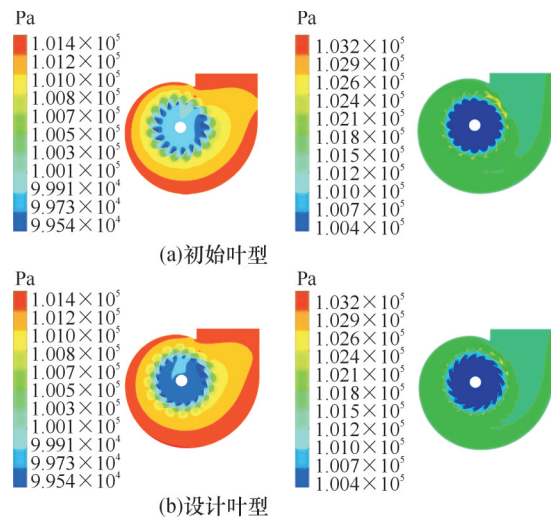


图12 基于速度分布方法的设计叶型和初始叶型流场分布<sup>[59]</sup>

Fig.12 Flow field distribution of initial blade geometry and designed blade geometry based on velocity distribution method<sup>[59]</sup>

刘阳等<sup>[60]</sup>设计了一种S型仿生叶片,能够有效改善非工作出口侧流动状态,反转时叶轮叶顶侧流动分离得到有效抑制,漩涡强度显著减小,采用优化的S型仿生叶片能够在保证可逆多翼离心风机正转气动性能的同时,使得反转风量增加10.8%。王加浩等<sup>[61]</sup>以C型启动时鱼体中弧线为基准,设计了具有仿生中弧线和鱼体轮廓特征的耦合叶片,如图13所示,该叶片具有更好的引流

导向作用,叶间流道的低速分离旋涡明显减小,有效缓解了尾流与蜗舌、蜗壳之间的非定常相互作用,采用该叶片的多翼离心风机的风量增大了8.3%,噪声下降了1.1 dB(A)。

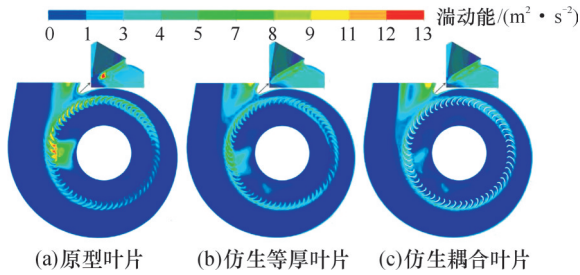


图13 三种叶片湍动能分布<sup>[61]</sup>

Fig.13 Three types of blade turbulent kinetic energy distribution<sup>[61]</sup>

### 3.3 组合优化及其他因素对风机升压性能的影响

孟永哲等<sup>[62]</sup>对多翼离心风机的叶轮和蜗壳进行模块化设计,基于叶轮与蜗壳匹配设计的多翼离心风机旋涡尺度与强度均有所减小,在全工况条件下加权风量增加了3.23%。刘阳等<sup>[63]</sup>采用分组优化设计的方法研究了叶轮、蜗壳型线、蜗舌和集流器对单风机以及风机盘管整机气动性能的影响,发现基于贝塞尔曲线的吸力面仿鱼形叶片设计对风机盘管整机性能的影响度最高,有效抑制了叶片吸力面上的流动分离,如图14所示,采用分组优化设计之后的单风机风量提高了18%,效率提高了2.8%;风机盘管整机风量提高了11.2%,效率提高了0.83%。

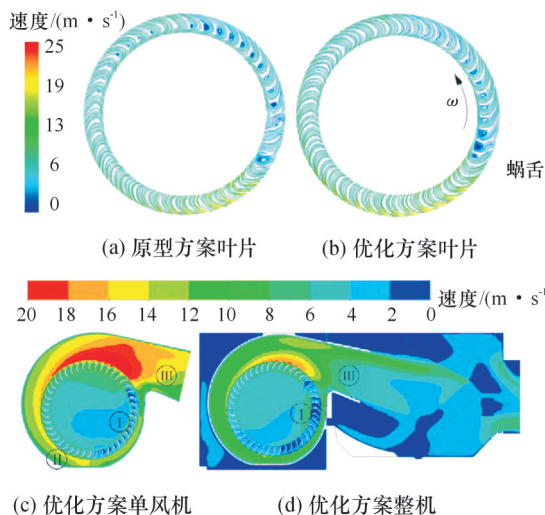


图14 基于贝塞尔曲线的仿鱼形叶片风机流场分布<sup>[63]</sup>

Fig.14 Flow field distribution of fan with fish-shaped blade based on Bessel curve<sup>[63]</sup>

MICHALSON等<sup>[64]</sup>将电机设计到风机的吸入室,发现电机帽插入到吸入室总深度的50%以上时,吸入室的侵入深度才会对风扇的性能产生

轻微影响,外壳的最佳尺寸接近风扇直径的1.35倍。LIU等<sup>[65]</sup>研究了风机在不同海拔下的性能,发现随着海拔高度的增加,风机输出容积流量略有减小,叶片压力面与吸力面的静压差减小,叶片负荷减小,风机输出静压和轴功率线性减小,风机静压效率非线性降低。QIU等<sup>[66]</sup>提出了一种混合不确定性分析方法,计算了叶轮机械流体动力学失效概率区间,结果表明,提高叶轮机械关键参数的不确定度可显著提高叶轮机械流动性能的可靠性。蒋博彦等<sup>[67]</sup>研究了风机加工制造中组合式切割法所得方案、单侧切割方案、收缩型方案对全工况气动性能的影响规律,如图15所示,发现该组合式切割所得型线非连续方案的叶轮效率、蜗壳静压转换能力相对于原型机的降幅反而更小,具有明显的性能优势。

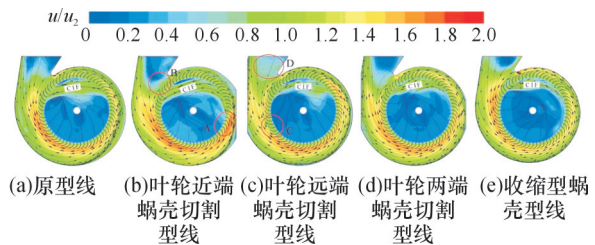


图15 叶轮流体高界截面流场分布<sup>[67]</sup>

Fig.15 Flow field distribution of high boundary section of rotating body<sup>[67]</sup>

小结如下:0区风机出入口设有阻火器,必将带来流场的扰动,国内外学者针对风机蜗壳及内部叶轮开展了几何形状优化设计工作,提升了风机性能,但对设置阻火器的0区风机流场优化的研究报道较少。因此,关于阻火器引起风机流场扰动的规律分析、0区风机整机的流场优化研究工作有待开展,以提高0区风机的全工况通气性能。

### 4 叶轮离心应力与振动研究

相较于普通风机,0区风机叶轮高速旋转与蜗壳间可能产生机械火花点燃源,目前国内外研究者通常采用有限元理论对普通风机叶轮开展应力与振动分析<sup>[68]</sup>。

曹海兰等<sup>[69]</sup>研究了叶轮前6阶固有频率和振型,把前6阶固有频率换算为对应的转速,使叶轮的运转速度远离临界速度,避免叶轮结构破坏。SUN等<sup>[70]</sup>研究发现,衬壁对风扇叶片的气动弹性稳定性有明显的影响,叶轮在制造过程中的部分焊接变形会导致叶轮变形。FAN等<sup>[71]</sup>研究了三个工程参数(扭转、扫掠、倾斜)对风机叶片气动性

能和结构性能的影响,如图16所示,发现扭转和扫掠叶片的轴向速度分布更加均匀,可显著提高总压比(范围约5%~15%),但强烈的叶尖泄漏涡流导致了过早的旋转不稳定。

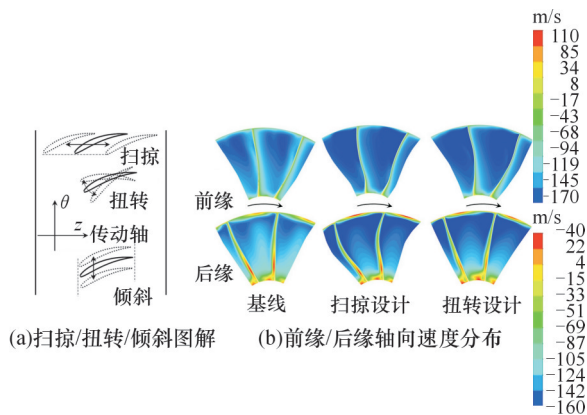


图16 扭转、扫掠、倾斜对风机叶片气动性能的影响<sup>[71]</sup>

Fig.16 Effect of twist, sweep and lean on aerodynamic performance of fan blades<sup>[71]</sup>

MOHAIDEEN等<sup>[72]</sup>通过优化叶轮零件的厚度,避开安全应力和应变极限,解决风扇质量大、易振动和故障的问题。YE等<sup>[73]</sup>研究了不同叶顶结构对流场、损失分布和噪声特性的影响,发现采用开槽叶尖可在一定程度上降低一阶模态下叶片的共振可能性。LIU等<sup>[74]</sup>研究了焊接变形和流体与结构相互作用引起的变形,讨论了焊接变形、塑性应变分布与固有变形的耦合关系,建立了热弹塑性有限元分析方法,如图17所示,为焊接风机及相关流体机械的变形控制提供了参考。

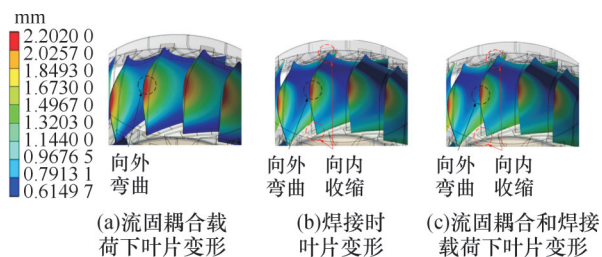


图17 叶片变形量分布<sup>[74]</sup>

Fig.17 Blade deformation distribution<sup>[74]</sup>

ZHANG等<sup>[75]</sup>研究了双级轴流风机的叶片载荷和振动特性,发现叶尖弯曲是导致叶根应力集中主要原因,叶尖形状会显著改变应力和幅频响应。ZHANG等<sup>[76]</sup>对轴流风机内相邻两动叶片异常挠度的影响进行了数值分析,发现叶片的变形分布受到气动载荷和离心载荷的双重影响,最大总变形均出现在叶尖,+9°叶片转子的最大应力值和变形量明显增大。ZHAO等<sup>[77]</sup>对风扇叶片断裂的根本原因进行了分析,发现扭转共振时引起的过大动应力是导致风机叶片疲劳断裂的根本

原因,如图18所示。

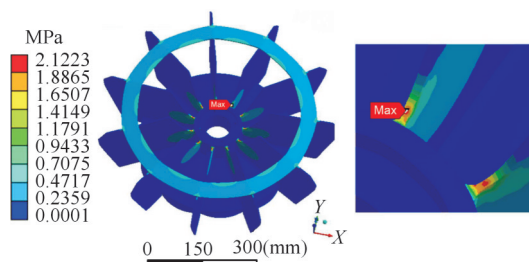


图18 叶片断裂应力分布<sup>[77]</sup>

Fig.18 Fracture stress distribution of blade<sup>[77]</sup>

小结如下:国内外学者针对风机叶轮开展了大量应力分析与振型分布的研究,对0区风机叶轮的强度分析研究具有借鉴意义。鉴于叶轮结构与流场的耦合关系,可建立0区风机叶轮多物理场有限元模型,研究叶片变形与流场相互作用的流固耦合问题的计算方法,优化叶轮零件的结构参数,合理设定安全应力和应变极限,同时建立多工况叶轮振动测试评价方法,以解决0区风机叶轮的振动和形变引起机械火花燃爆问题。

### 5 风机轴封技术研究

风机的轴封对风机的密封至关重要,0区风机的轴封更要求特殊设计,在此领域主要关注轴封材料的耐磨性<sup>[78-80]</sup>及失效原因<sup>[81-85]</sup>的分析。

XUAN等<sup>[86]</sup>研究了硫化硅橡胶与风扇叶片之间的高速刮擦行为,发现磨粒磨损和花纹磨损是主要的磨损机制,叶尖速度达到150 m/s是磨损的临界点。LI等<sup>[87]</sup>采用内窥镜和中空透明轴观察密封的失效过程,发现磁性流体密封达到临界速度时,界面处的流动由层流转变为湍流,导致明显的分层波动,如图19所示,揭示了密封失效

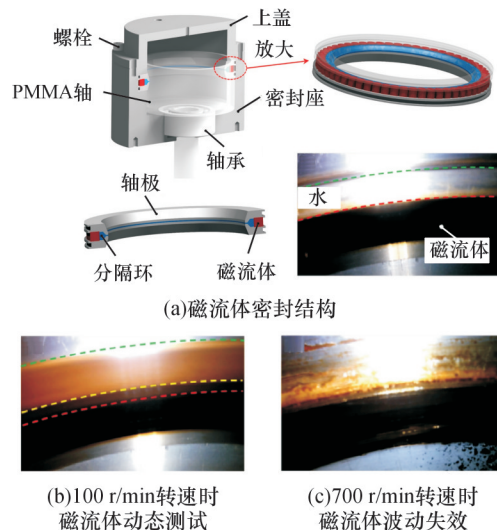


图19 磁性流体密封结构与测试<sup>[87]</sup>

Fig.19 Magnetic fluid seal structure and testing<sup>[87]</sup>

的关键诱发因素。

HUANG等<sup>[88]</sup>研究了聚四氟乙烯旋转唇型密封泄漏模型,估算了密封的磨损量,并利用该模型评估磨损系数的变化和优化了密封唇的反向泵送速率。SHIMADA等<sup>[89]</sup>在固定环密封风机环与风机罩之间的尖端间隙中应用迷宫密封,发现应用后比传统风机具有更高的风机性能和更低的风机噪声。LI等<sup>[90]</sup>对高转速下碳环密封的泄漏磨损特性进行了试验研究,获得碳密封寿命预测的拟合公式。OUTIRBA等<sup>[91]</sup>研究了碳纤维刷式密封的耐久性,开发了半经验性能预测模型,发现润滑油的存在延长了密封寿命,如图20所示,分析样品性能下降的原因主要是碳纤维被连根破坏。

TENG等<sup>[92]</sup>研究了双面螺旋槽气端面密封的结构形式对气体密封动态性能的影响,发现双面开槽法既有较高的气膜承载能力,又有较高的气膜刚度。PARMAR等<sup>[93]</sup>设计并测试了楔形极

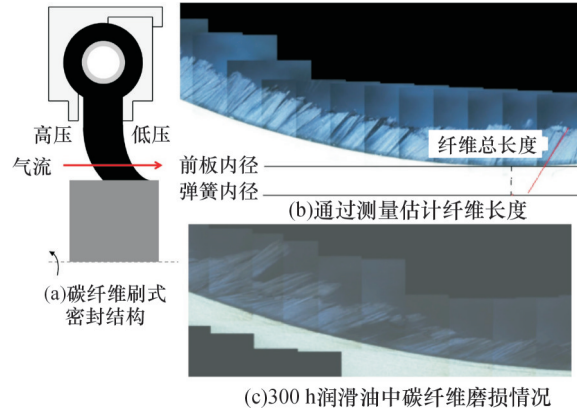


图20 碳纤维刷式密封结构与测试<sup>[91]</sup>

Fig.20 Carbon fiber brush seal structure and testing<sup>[91]</sup>

片、最佳长径比、较高场梯度和较高流体磁化强度的组合轴封可提高流体塞的保压能力。HU等<sup>[94]</sup>提出了一种面向干气密封状态监测的端面沟槽结构,利用监测凹槽可以感应到端面接触的特征,实现了干气密封的异常监测,如图21所示。

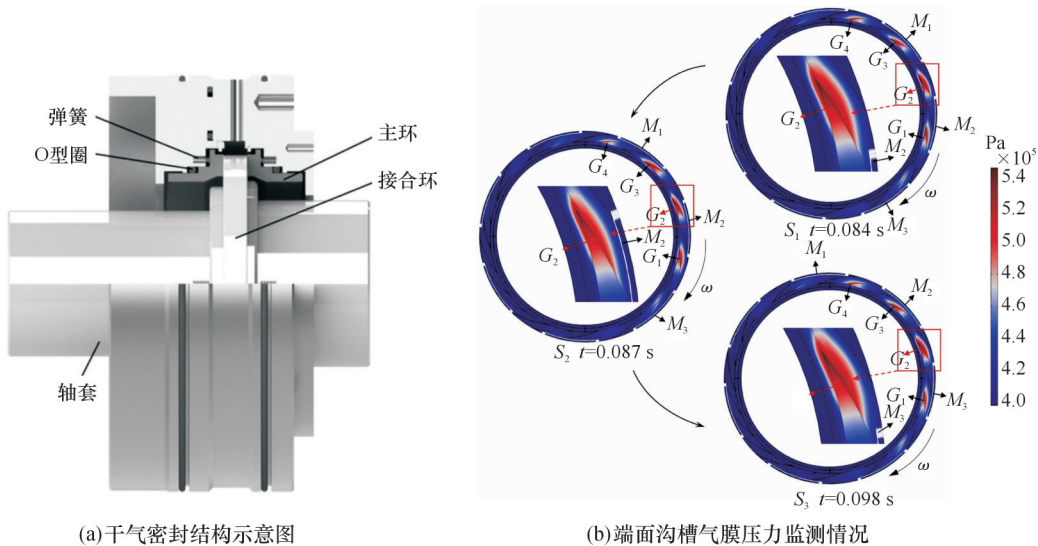


图21 干气密封结构与压力状态监测<sup>[94]</sup>

Fig.21 Dry gas seal structure and pressure state monitoring<sup>[94]</sup>

小结如下:0区风机整体97%以上部件为金属材料,风机轴封作为含有非金属材料的部件,是0区风机燃爆工况下的最薄弱部件。国内外学者针对橡胶、碳化硅、聚四氟乙烯、碳纤维等转动轴封材料开展研究,主要目标是减少轴封磨损与保障轴封密封性能,但对于轴封相关静电与抗爆炸冲击性能的研究报道较少。因此,关于高静电抗爆炸冲击轴封材料的研制有待开展,同时基于该材料的轴封结构设计有待研究,以实现0区风机的爆炸安全与高效密封。

## 6 阻火器及阻火性能测试方法研究

0区风机出入口需要设置阻火器<sup>[95-97]</sup>,以阻止

风机内部火焰向管道内传播。阻火器属于单体静态设备,一般开展静态气体燃爆实验须进行阻火性能测试。对于集成阻火器的0区风机整机,需提出合适的抗爆性能测试方法,以解决0区风机动态运转工况下抗爆阻火性能评估问题。

SUN等<sup>[98]</sup>搭建了阻火器组成的实验系统,研究了物理参数对丙烷、乙烯和氢气/空气混合物火焰传播和熄灭过程的影响。BAO等<sup>[99]</sup>设计了DN50阻火器爆轰火焰侵彻特性及失效机理实验装置,用高速摄像机直接捕捉阻火器灭火过程的两种失效模式。WANG等<sup>[100]</sup>在丙烷-空气可燃混合物的圆形管道中进行了卷曲带式阻火器爆燃火焰的实验,如图22所示,推导出阻火器性能与

隔爆速度之间关系的两个经验公式,可用于预测卷曲带状阻火器的性能。

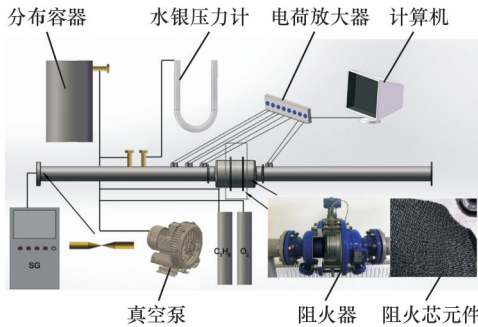


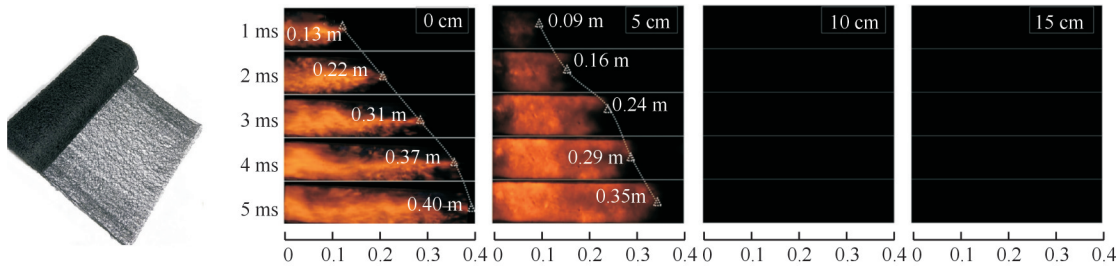
图22 卷曲带式阻火器及爆炸测试装置<sup>[100]</sup>

Fig.22 Crimped belt flame arrester and explosion test device<sup>[100]</sup>

HAMZAH等<sup>[101]</sup>研究了陶瓷泡沫对铝粉爆炸的影响,发现与非涂层陶瓷相比,镍陶瓷壁相互连接的微网络结构有利于熄灭火焰,最大超压显著

降低了约10%。CHEN等<sup>[102]</sup>通过实验研究了球形陶瓷颗粒对密闭管道中预混甲烷-空气火焰传播的影响,发现直径3mm的陶瓷颗粒对火焰传播和压力积聚的抑制效果最好。YUAN等<sup>[103]</sup>研制了一种可完全淬灭爆炸火焰的新型三维网状多孔火焰防爆材料,如图23所示,发现材料长度为10cm时无火焰传播,管道上下游的最大爆炸超压衰减比分别为87.5%和82.5%,可将其作为燃料油领域防爆材料。

小结如下:国内外针对阻火器及阻火性能测试方法的研究报道较多,主要通过固定管道或容器开展静态气体燃爆实验,对动态运转风机的爆炸测试研究则为空白。因此,0区风机动态循环式气体燃爆测试系统有待研制,爆炸测试方法及性能评估标准也有待建立,以准确评判0区风机的抗爆阻火性能。



(a)三维网状多孔材料

(b)三维网状多孔材料气体燃爆阻火测试

图23 三维网状多孔材料及其气体燃爆测试过程<sup>[103]</sup>

Fig.24 Three dimensional mesh porous material and gas explosion test process<sup>[103]</sup>

## 7 结论与展望

目前,国内外关于0区防爆风机的系统性研究未见报道,通过技术分解后,气体燃爆规律、风机流场优化计算、叶轮离心应力与振动、风机轴封技术以及阻火器爆炸性能测试等5方面关键技术的研究鲜见报道,仅能检索到与关键技术类似的相关工作。基于此,未来爆炸0区防爆风机技术的研究可从以下方面展开:

1)建立0区风机爆炸测试方法。相对于静态预混燃爆测试,风机动态燃爆测试更加复杂,建立爆炸0区风机燃爆测试方法与装置是研发0区风机的前提。一方面需搭建循环回路式测试管道,配置成套的点火与检测装置;另一方面需建立0区风机不同运转状态下的燃爆测试方法,覆盖0区风机正常运转、变频运行及静置状态,以全方位评估0区风机抗爆炸冲击性能。

2)揭示0区风机内部腔体气体燃爆规律。风机内部腔体动态与静态的燃爆规律是0区风机研发的基础数据,相对于管道和储罐内气相燃爆,风

机叶轮具有曲率通道且燃爆过程存在与旋转流场的相互耦合作用,风机内部腔体气体燃爆规律更加复杂。需建立气体燃爆反应、物质传递、旋转流场等多物理场计算大模型,揭示燃爆过程火焰传播演化规律,验证实验结果并修正计算模型,得到风机内部腔体气体燃爆计算方法。

3)优化0区风机整体流场。0区风机出入口设有阻火器,带来流场的扰动和阻力降的增加,风机整体流场的优化是0区风机的升压性能设计的关键。要优化0区风机整体流场,一是要开展阻火器引起风机流场扰动的规律分析,提出降低阻火器流场扰动的方法;二是要建立包含阻火器、叶轮与蜗壳的风机整机流场计算模型,研究优化风机叶轮线型与蜗壳结构参数,以提高0区风机的全工况通气性能。

4)提高风机叶轮强度。0区风机叶轮强度提高是0区防爆风机安全性能设计的关键,相较于普通风机,0区风机叶轮高速旋转与蜗壳间可能产生机械火花点燃源。要提高风机叶轮强度,一是要研究叶片变形与流场相互作用的流固耦合问

题的计算方法,优化叶轮的线型结构参数,确定安全应力和应变极限,解决0区风机叶轮的振动和形变计算问题;二是要建立0区风机叶轮不同运转状态下的振动测试评价方法,覆盖叶轮动平衡、超速以及风机入口关闭状态,多工况评估0区风机叶轮强度性能。

5)开发0区风机用安全轴封。风机轴封作为含有非金属材料的部件,是0区风机燃爆工况下的最薄弱部件。国内外学者针对轴封材料的耐磨损与保障密封性能开展了研究,但缺少轴封相关导静电与抗爆炸冲击材料和结构的研究。要研发0区风机用安全轴封,一是要建立安全轴封材料的性能评价方法;二是要开展基于橡塑弹性体材料的高导静电抗爆炸冲击轴封材料的研发制备工作;三是要根据轴封材料特性、安全抗爆要求和密封性能要求,研发适配轴封结构,形成安全轴封设备。

随着“碳达峰、碳中和”发展目标的提出,VOCs治理系统应用场景将愈加广泛,其系统安全保障的需求日益迫切。爆炸0区防爆风机是VOCs系统重要升压动设备,目前0区风机相关技术的研究报道较少,但国内外学者已经从曲率/螺旋管道气相燃爆、风机叶轮/蜗壳流场优化提升、叶轮离心应力与振动优化、风机轴封材料与结构研究以及阻火器爆炸测试方面进行了有益尝试和探讨,相信通过多项关键技术的突破,可实现国内产品零的突破,提高化工行业VOCs治理系统机械安全防爆水平,保障化工行业“碳达峰、碳中和”目标的顺利推进。

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