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热泵技术专栏

中大容量工业余热高温热泵的压缩机技术现状

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摘 要 热泵技术是一种节能技术,能够有效应对全球变暖,降低碳排放。工业热泵回收供热过程的废热加热水或空气,可减少电力消耗及碳排放。工业热泵节能环保,供热稳定,已广泛应用于生产及生活的各个阶段。分析了国内外工业余热高温热泵的压缩机类型及特点,针对中大容量的双螺杆压缩机及离心压缩机,分析其应用及技术现状。螺杆式热泵压缩机在高蒸发温度时应采用开启式结构,高冷凝温度时可采用高速无油方案;离心式热泵压缩机除高效的叶轮外,应关注耐高温电机与无油润滑轴承。螺杆式水蒸气压缩机关注转子热变形及轴封问题,向大温升方向发展。

关键词 高温热泵;双螺杆压缩机;离心压缩机;水蒸气压缩机

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Development Status of Compressor Technology for Medium and Large Capacity Industrial High-Temperature Heat Pumps

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Abstract Heat pump technology is an energy-saving solution that could potentially combat global warming and reduce carbon emissions. Industrial heat pumps recover waste heat from the heating process to heat water or air, thereby reducing electricity consumption and carbon emissions. Industrial heat pumps are energy-saving, environmentally friendly, and provide stable heating. They have been widely used at all stages of production and life. This study analyzes the compressor types and characteristics of domestic and international high-temperature heat pumps (HTHP) that recover industrial waste heat and analyzes their application and technical status with a focus on twin-screw and centrifugal compressors. Twin-screw heat pump compressors should adopt an open structure when the evaporation temperature is high, and high-speed and oil-free design can be used when the condensation temperature is high. In addition, centrifugal heat pump compressors should prioritize highly efficient impellers, high-temperature-resistant motors, and oil-free lubricated bearings. Screw steam compressors need to solve the problems of rotor thermal deformation and shaft seal, and target for large temperature lifts.

Keywords high-temperature heat pump; twin-screw compressor; centrifugal compressor; steam compressor

为应对全球变暖、气候变化的挑战,我国确立了2030 年之前实现碳达峰,2060 年实现碳中和的目标。我国工业能耗占全社会总能耗的 60%,其中 50%以上是热能。燃煤锅炉废气污染严重,燃气锅炉供气不稳定,电锅炉耗电量巨大,对电网负荷冲击高,需要新型的供热供气装置[1-3]。我国工业消耗的能源有 50%以上以废水和废气的形式转化为余热,其中仅 30%被重新利用,能源利用效率低[4-5]。热泵技术可利用工业余热或可再生热能实现工业热能的清洁高效供给[6-8]。

工业领域高温热泵主要用于制备热水(热空气)和水蒸气(蒸汽)。制备热蒸汽的高温热泵系统一般有两种技术途径[9-12]:一种是在热泵系统的基础上增加蒸汽增压系统以提高蒸汽温度,系统中存在热泵压缩机与水蒸气压缩机;另一种则是直接由热泵系统制备高温蒸汽,系统中仅存在热泵压缩机。宽工况高效可靠的压缩机是高温热泵系统的重大设备保障,是热泵机组的核心部件。本文回顾了国内外高温热泵产品的发展现状,对中大容量的高温热泵/蒸汽压缩机的技术进行分析,为后续高温热泵/蒸汽压缩机的发展提供借鉴与指导。

1 中大容量热泵/蒸汽压缩机

欧美日等发达国家较早开始工业热泵的技术开发

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与商业化,我国发展相对较晚,且在压缩机与工质领域技术相对落后。常用压缩机的制热量范围如表 1 所示。其中,中大容量的压缩机主要为双螺杆式及离心式压缩机,两者既可做热泵压缩机,也可做蒸汽压缩机。

表 1 常用压缩机特性[13]

Tab.1 Characteristics of the common heat pump[13]

压缩机类型	常用制热量范围/kW
往复活塞式	0.3~500
滚动转子式	0.5~15
涡旋式	3~100
螺杆式	100~1 500
离心式	>300

1.1 国外高温热泵/蒸汽压缩机

部分国际市场的高温热泵系统用高温热泵/蒸汽压缩机产品如表 2 所示。其主要产品为双螺杆热泵压缩机、离心式热泵压缩机及螺杆式水蒸气压缩机。

1.1.1 双螺杆式热泵/蒸汽压缩机

热泵系统用的双螺杆压缩机为喷油双螺杆压缩机,可在压缩过程中喷油。螺杆压缩机可带液运行,可用于压缩水蒸气。

Combitherm 的 HWW9583 使用 Bitzer 的半封式双螺杆压缩机,工质为 R1234ze 或 R1233zd(E),可实现 17% ~ 100% 的无级容量调节。制热能力从 0.3 MW(1 台)至 3.3 MW(3 台)。工质为 R1234ze 时,最高供热温度为 95 ℃;工质为 R1233zd(E)时,最高制热温度可达 120 ℃[14-15]。Johnson Controls 的

表 2 部分国外市场的高温热泵/蒸汽压缩机

Tab.2 The HTHP and steam compressors in some international markets

品牌	产品	压缩机类型	制冷剂	最大制热量/kW	热汇供应温度/℃	参考文献
Combitherm	HWW 9583 R1234ze	双螺杆压缩机	R1234ze	937	最高 95	[14-15]
	HWW 9583 R1233zd(E)	双螺杆压缩机	R1233zd(E)	462	最高 120	
Johnson Controls	SABROE heat pump	双螺杆压缩机	R717(NH_3)	1 800	最高 90	[16]
	Titan OM HP	多级离心压缩机	R134a	20 000	最高 90	[17]
Ochsner	IWWDS ER3b	双螺杆压缩机	ÖKO 1	750	最高 130	[18-19]
	IWWDS/ISWDSER3c4	双螺杆压缩机	ÖKO 1	750	最高 125	
	IWWDSS R2R3b	双螺杆压缩机	ÖKO 1/R134a	750	最高 130	
Rank	HP 1~4	双螺杆压缩机	R245fa、R1336mzz(Z)	2 000	100~140	[20]
SRM	SRM prototype	双螺杆压缩机	R718(water)	250	最高 165	[21]
KOBELCO	SGH120	双螺杆压缩机	R245fa	380	100~120	[22-25]
	SGH165	双螺杆压缩机	R134a/R245fa	660	135~175	
	HEM-HR90	双螺杆压缩机	R134a/R245fa	230	70~90	
	HEM-90A	双螺杆压缩机	R134a/R245fa	230	65~90	
	MSRC 160L	双螺杆压缩机	R718(water)	800	145~175	
GEA	GEA Grasso FX P	双螺杆压缩机	R717(NH_3)	5 825	最高 90	[26-27]
Aneo Industry	SPHP	活塞/离心压缩机	R717/R718	10 000	最高 150	[28]
Mitsubishi Heavy	ETW-S	多级离心压缩机	R134a	627	最高 130	[29]
Ecop	RHP K7	离心压缩机	ecop fluid 1	700	最高 150	[30]
Enertime	热泵	离心压缩机	R1336mzz(Z)、R1233zd(E)	10 000	最高 160	[31]
Turboden	LHP	离心压缩机	R600a	40 000	最高 250	[32]
Siemens Energy	高温热泵	离心压缩机	R1233zd(E)、R1234ze(E)	70 000	最高 160	[33]

SABROE heat pump 采用 R717 工质,最高供热温度为 90 ℃,最大制热量为 1 800 kW[16]。同样,GEA Grasso FX P 热泵系统采用 R717 工质,最高压力为 6 300 kPa,最高供热温度为 90 ℃[26]。

Ochsner 的 IWWDS ER3b 和 IWWDS/ISWDS ER3c4 使用 ÖKO 1 制冷剂,最高制热量为 750 kW,最高温度分别为 130 ℃和 125 ℃。IWWDSS R2R3b 双螺杆热泵系统,工质为 ÖKO 1 和 R134a,最高供热温度可达 130 ℃[18-19]。Rank 的 HP 系列采用增加内部换热器的单级压缩循环,可用工质为 R245fa、R1336mzz(Z)和 R1233zd(E),供热温度为 100~140 ℃,最高制热量为 2 000 kW,可用于区域供暖[20]。

蒸汽具有高潜热和传热性能,在巴氏杀菌、化学分离及烘干等行业应用广泛。为获得微压蒸汽,在热泵系统的基础上增加闪蒸罐。获得低压蒸汽时,需增加水蒸气压缩机,对微压蒸汽进行加温加压。蒸汽的制备可采用单级压缩、多级压缩或复叠循环,配合闪蒸罐、水蒸气压缩机获得。水蒸气压缩机是蒸汽制备过程的重要设备[34]。

SRM 的 R718 水蒸气压缩机,体积流量为 6 000 m^3/h,在 75~120 ℃的蒸发温度下运行,最高压比为 10。用于 R717/R718 复叠热泵系统,最高可获得 165 ℃蒸汽[25]。

KOBELCO 的蒸汽发生热泵 SGH120 和 SGH165 可替代低压蒸汽锅炉。SGH120 蒸汽发生器使用单级压缩循环,增加中间换热器和经济器以增强系统性能,热泵压缩机为两级压缩机,采用 R245fa 工质。水经过冷凝器及闪蒸罐后获得 100~120 ℃的饱和蒸汽。SGH165 与 SGH120 在循环工质与蒸汽产生过程存在差异[22-23]。SGH165 采用 R245fa 和 R134a 的混合制冷剂,并在闪蒸罐后增加双螺杆水蒸气压缩机组以增温增压。KOBELCO 的 MSRC 160L 为机械蒸汽再压缩系统,主要由无油双螺杆压缩机和水汽分离器组成[24]。通过向螺杆压缩机喷水以降低转子热变形,保证转子间、转子与机壳间的间隙。此外,KOBELCO 的 HEM-90A 空气源热泵用两级螺杆压缩机实现最高温度为 90 ℃的供热,采用 R134a 和 R245fa 工质,而 HEM-HR90 仅为单级压缩机[25]。

1.1.2 离心式热泵/蒸汽压缩机

离心式压缩机具有高效率及无油压缩等特点,已广泛应用于大容量制冷和热泵领域。

Johnson Controls 的 Titan OM HP 热泵系统采用多级离心压缩机,采用 R134a 工质,最高供热温度为 90 ℃,最大制热量为 20 MW[17]。Mitsubishi Heavy 的 ETW-S 同样采用 R134a 的多级离心压缩机,最高转速为 42 000 r/min,使用跨临界循环系统,最高供热温度为 130 ℃,最大制热量为 627 kW[29]。

Enertime 的热泵采用 R1336mzz(Z)、R1224yd(Z)、R1233zd(E)等工质,最高转速为 20 000 r/min,最高压比为 3.2。Siemens Energy 的高温热泵采用 R1233zd(E)、R1234ze(E)为工质,两者的最高供热温度均为 160 ℃[31]。Turboden 的 LHP 大型热泵应用在造纸厂取代天然气锅炉,回收废水废气,采用 R600a 制冷剂,最高供热温度为 250 ℃,最大供热量为 4 MW[32]。

1.2 国内高温热泵/蒸汽压缩机

国内高温热泵发展较晚,主要集中于双螺杆式与离心式压缩机,有部分小容量的涡旋压缩机。国内市场的高温/蒸汽热泵系统用压缩机如表 3 所示。麦克维尔与美肯均使用复叠热泵,使用涡旋压缩机,工质为 R410A 与 R134a。其中麦克维尔的 90 ℃高温热泵机组最大制热量为 56 kW,而美肯的变频复叠高温热泵最高供热温度为 85 ℃。英华特则研发了高温热泵用 R515B 涡旋压缩机,使用 POE 润滑油,供热温度为 80~100 ℃,最大制热量为 39 kW。诺通科技有两款产品使用复叠热泵,其中 90 ℃直流变频高温热水机采用 R410A 与 R134a 工质,最大制热量为 60 kW,最高可供 90 ℃热水;120 ℃直流变频蒸汽机则采用 R410A 与 R245fa 工质,最大制热量为 120 kW,最高可供 120 ℃热水。其高温水源热泵可选用涡旋或螺杆压缩机,实现最高温度为 150 ℃的供热。

国内使用双螺杆式与离心式压缩机的热泵较多,克莱门特、约克、双良、汉钟精机、雪人股份、必信及顿汉布什等企业均使用双螺杆热泵压缩机,大容量的离心式压缩机在冰轮环境、格力电器及荏原等企业的产品中已见应用。

克莱门特的超高温水源热泵机组使用 R245fa 的双螺杆压缩机,最高供热温度为 120 ℃,最大制热量为 2 000 kW。约克的 HPS(60)螺杆式高速永磁变频高温热泵机组和雪人股份的 Powerbox-SRM 系列开启式螺杆高温热泵机组均使用 R717 作为工质,最高供热温度为 90 ℃。汉钟精机的 RC2-G&T 系列双螺杆压缩机分别使用 R134a 和 R245fa。RC2-G 系列极限冷凝温度可达 95 ℃,最高回收余热温度可达 55 ℃,最高出水温度可达 90 ℃。RC2-T 系列冷凝温度可达 125 ℃,最高回收余热温度为 85 ℃,最高出水温度为 120 ℃,实现高品位余热回收。LT-S-H(A)单机双级高温热泵压缩机在大压差、大压比工况下具有高效率、高可靠性,应用于水(地)源热泵,最高出水温度为 90 ℃,满足供暖及其他工业用热需求,应用

于空气源热泵最低环境温度可低至-55 ℃,可使用多种工质。

表 3 国内市场的高温热泵系统用压缩机

Tab.3 The high temperature heat pump in domestic markets

品牌	产品	压缩机类型	制冷剂	最大制热量/kW	热汇供应温度/℃
麦克维尔	90 ℃高温热泵机组	涡旋压缩机	R410A/R134a	56	最高 90
美肯	85 ℃高温热泵	涡旋压缩机	R410A/R134a	—	最高 85
英华特	YW470K1-100	涡旋压缩机	R515B	39	80~100
诺通科技	90 ℃高温热水机	涡旋压缩机	R410A/R134a	60	最高 90
	120 ℃蒸汽机	涡旋压缩机	R410A/R245fa	120	最高 120
	NT-HTHP-SHHP	涡旋、螺杆机	—	1 700	最高 150
	热泵蒸汽发生系统	双螺杆压缩机	—	—	最高 180
	余热源高温离心热泵	离心压缩机	—	10 000	最高 100
克莱门特	超高温水源热泵机组	双螺杆压缩机	R245fa	2 000	最高 120
约克	HPS(60)高温热泵机组	双螺杆压缩机	R717	1 900	最高 90
双良节能	高温螺杆式水源热泵机组	双螺杆压缩机	R134a	—	最高 82
汉钟精机	RC2-G&T 系列	双螺杆压缩机	R134a、R245fa	2 500	最高 120
	LT-S-H 系列	两级双螺杆	R134a、R515B	820	最高 90
雪人股份	Powerbox-SRM	双螺杆压缩机	R717	6 500	最高 90
必信	超高温热泵机组	双螺杆压缩机	HFC、HFO	2 000	最高 180
顿汉布什	WCHXHP	双螺杆压缩机	R134a、R245fa	3 400	最高 120
荏原	RTGF 系列	离心式压缩机	—	—	最高 178
格力电器	CVP 系列	离心式压缩机	R1233zd(E)	10 000	最高 120
冰轮环境	GHWS-HFO 高温水汽一体机	离心式压缩机	R1336mzz(Z)	10 000	最高 128
	HD-宽温域离心机组	离心式压缩机	R245fa	10 000	100~112

冰轮的 HD-宽温域离散余热相变提质离心机组与 GHWS-HFO 高温水汽一体机最大制热量为 10 MW,最高供热温度为 128 ℃,分别采用 R245fa 与 R1336mzz(Z)工质。格力 CVP 系列离心热泵采用 R1233zd(E)工质,最高供热温度为 120 ℃,最大制热量为 10 MW。

2 双螺杆压缩机技术

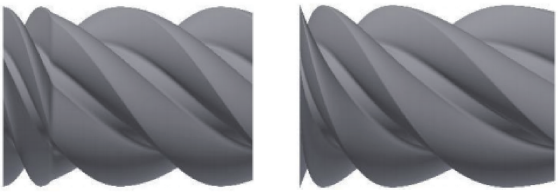
双螺杆压缩机属于容积型回转式压缩机,具有结构简单紧凑、易损件少、可带液压缩等优点。在热泵系统中根据制冷剂及喷液的不同一般分为喷油双螺杆热泵压缩机及喷水水蒸气压缩机。

2.1 型线及转子研究

双螺杆式压缩机的型线和转子几何从根本上决定了螺杆压缩机的性能及可靠性。优秀的转子型线及几何能够减少泄漏、摩擦。众多研究机构及企业都拥有自己的型线,例如 SRM‘D’型线、复盛型线、GHH 型线、日立型线及‘N’型线等[35]。目前,一种新的设计趋势是使用样条曲线、贝塞尔曲线或非均匀有理 B 样条曲线来构成转子型线,能够较好地设计双螺杆转子[36]。

双螺杆转子的螺距一般为固定值,而近年来许多研究者开始设计并研究变螺距双螺杆转子。变螺距双螺杆转子能够增加排气面积,具有更高的等熵效率,但存在加工困难的情况。双螺杆压缩机的转子导程变化可分为多段导程转子与渐变导程转子。变导程转子如图 1 所示。多段等螺距可以增加排气面积,减小流动损失,内容积比可达 6.5,具有更高的效率[37-39]。此外,相交轴锥螺杆压缩机的研究及产品增加,其具有泄漏线短、无泄漏三角形及同向热膨胀等优点,内容积比高达 9.0 以上。当压比为 21 时,等熵效率为 75%,容积效率为 95%;压比高达 41 时,等熵效率仍高于 45%,容积效率高于 75%[40-42]。

转子间、转子与壳体间的间隙影响双螺杆压缩机



(a) 多段导程转子　　(b) 渐变导程转子

图 1 变导程转子

Fig.1 Screw rotor with variable lead

的性能,间隙较大会导致压缩机的容积效率和绝热效率严重下降。影响转子变形最大的因素是温度,研究转子热变形,给定更为合理的转子间隙分布能够提高压缩机效率[43-44]。可通过转子热变形反向修正型线或增加涂层提高压缩机性能。转子热变形可通过热力学模型或 CFD 模型获得热变形,其中 CFD 模型可采用热-固耦合或热-流-固耦合获得更准确的转子热变形[45-47]。对转子进行表面处理,如硬质阳极氧化、镀铬、电镀或 PTFE 涂层,减小间隙并减少摩擦[48]。Sun Shizhong 等[49]将耐磨涂层应用于转子表面,喷涂耐磨涂层后,容积效率及制冷量显著增加。

2.2 变频变容技术

螺杆压缩机的容积调节一般包括启停调节、滑阀调节及变频调节等。启停调节较为简单,即根据气量需求,进气阀根据控制自动调节阀的开闭,减少压缩机排气波动。变频调节通过调节压缩机转速,从而改变排气量,该技术调节范围广,能够提高一些负载下的能效[50-51]。滑阀调节为传统的容量调节方式,由容积滑阀、油活塞及电磁阀构成,通过调节有效压缩的螺杆长度来调节有效工作容积,调节范围为 50%~100%。

Sun Shizhong 等[52]对比了滑阀调节与变频调节两种能量调节方式,变频调节在满负荷情况有所下降,但部分负荷性能上 COP(coefficient of performance)增加。Wang Yu 等[53]建立了热泵用双螺杆压缩机内容积比与年冷热负荷需求的最优匹配策略,较传统匹配方法 COP 提高了 6%。通过容积滑阀调节内容积比、通过变频调节气量的变频变容螺杆制冷压缩机,实现了全工况下的能力适配与压比匹配,特别适用于高负荷及宽工况的热泵系统。变频变容的制冷螺杆压缩机如图 2 所示。

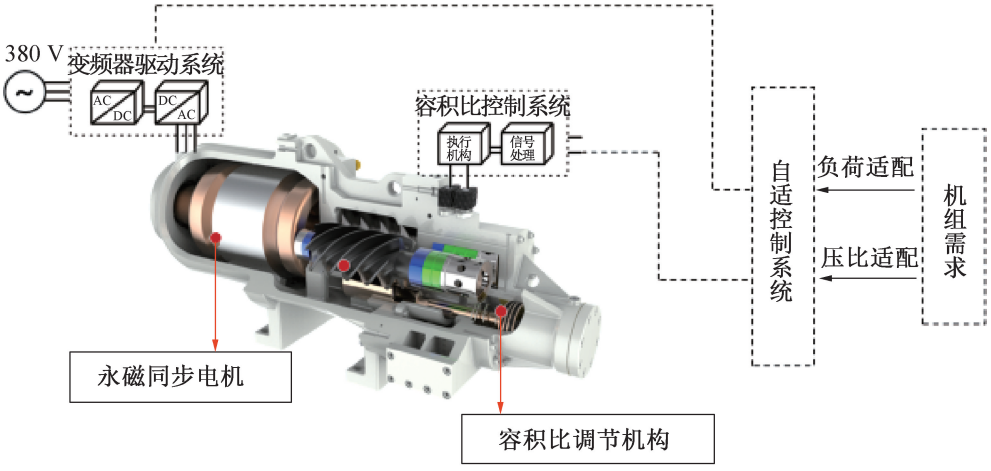


图 2 变频变容螺杆压缩机

Fig.2 Variable speed screw compressor with variable volume ratio

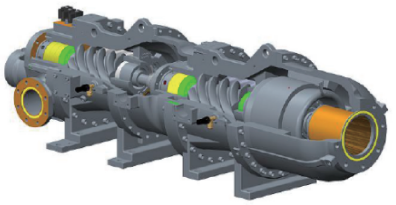
2.3 两级压缩、中间补气

单级双螺杆压缩机在大压比、高温升的严苛工况下,由于进出口的大压差会导致压缩机的泄漏、摩擦及磨损的增加,影响压缩机性能。针对上述工况,单机双级双螺杆压缩机可满足工况要求,性能表现良好[54-56]。且单机双级压缩机可在级间连接腔布置补气口,实现两级压缩机中间冷却的目的,节省压缩机功率,增加制冷量。

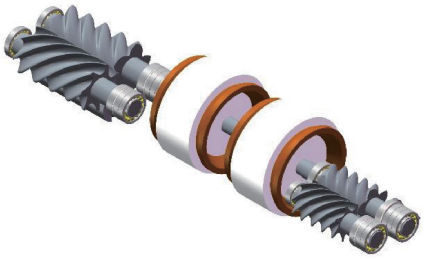
Wu Huagen 等[57]对单级双螺杆压缩机的补气进行研究,固定位置的补气口存在最佳补气压力,而补气压力固定时存在最佳补气位置,能够最大程度提高压缩机效率。将补气技术应用于单机双级双螺杆中,格力新研发的 147 kW 螺杆冷水机组制冷量提高 11%,COP 增大 8%,制冷机最高 COP 达 7.17[55-56]。

目前,单机双级双螺杆制冷压缩机主要为串联式,根据控制电机的数量主要有两种形式,其结构如图 3 所示。采用单电机时,高压、低压级阳转子通过一根轴与电机相连;采用双电机时,高压、低压级阳转子分别与其控制电机相连。

由于高温热泵的蒸发温度高,在高温时压缩机排



(a) 单电机



(b) 双电机

图 3 单机双级双螺杆制冷压缩机

Fig.3 Two-stage twin screw refrigeration compressor for one machine

气温度高应考虑电机的冷却,避免电机绕组升温超限。KOBELCO 的 HEM-90A 采用单机双级双螺杆压缩机,电机置于吸气侧,电机通过喷射闪蒸的制冷剂以降低电机温度[25]。对于更高温度的热泵压缩机,可采用开启式压缩机,GEA、SRM 以及汉钟精机均有此类产品。

2.4 喷液技术

在双螺杆压缩机腔内喷液,如润滑油、水和制冷剂等,可以提高压缩机性能,具有冷却、润滑、密封及降噪等作用[58-59]。高温热泵系统中的制冷剂压缩机运行过程中需要喷油以提高性能,蒸汽压缩机升温升压过程中进行喷水操作。

喷油或喷水的流量或喷液口尺寸存在最优值,一定的喷液量能够提高压缩机性能,喷液过多对压缩机性能影响较小,甚至可能导致性能变差[60-61]。对双螺杆压缩机的排气腔室和排气轴承喷低温润滑油能够提高其性能,且在两个转子同时喷油比单个转子喷油节能效果更好;而在进气口和吸气端轴承喷油则会降低压缩机性能[62-63]。对于水润滑空压机,推力轴承的总功率损失占总损失的比例超过 52%,而转子间的摩擦损失较小,这区别于喷油双螺杆压缩机[64]。

喷水双螺杆水蒸气压缩机不同于喷油双螺杆压缩机,其压缩机内压缩工质与喷液工质均为水,可采用进口喷液。进口喷液,压缩机进行湿压缩,降低排气温度,减少压缩功耗,且连续喷液可使容积效率提高 20%[65-68]。水蒸气压缩机最佳喷水量与旋转速度成正比,喷水量与压缩蒸汽的最佳质量比为 8.9%~10.4%,同时减少啮合线、齿顶与端面的泄漏能够提高水蒸气压缩机性能[69-70]。水蒸气压缩机应避免水蒸气和轴承润滑油的联通,轴封采用梳齿密封及碳环密封,且吸排气采用平衡管联通,以防止轴承失效[71]。

不同于喷水水蒸气压缩机,喷油双螺杆压缩机中润滑油与制冷剂为不同物质。润滑油与制冷剂的相互作用对压缩机和热泵系统的高效安全运行影响显著[72-73]。高温高压使润滑油黏度降低,减少了转动表面的油膜厚度,增加热泵压缩机功耗,降低高温热泵性能[74-75]。

采用制冷剂喷射无需考虑高温下油的黏度及兼容性,该方法可用于高速无油压缩机。Tian Yafen 等[76]研究了氨无油双螺杆压缩机喷射低浓度氨的性能,给出了喷嘴位置及喷液量的最优值;A. M. Ulrich 等[77]建立了喷液的氨无油双螺杆压缩机一维模型,分析了各种喷液参数对压缩机性能的影响。N. Stosic 等[78]研究了油、液体制冷剂、制冷剂蒸气、液-气混合物等对双螺杆压缩机性能的影响,研究发现小间隙情况下液体制冷剂喷射比喷油效果更好,且不同制冷剂喷射效果差异显著,如 R134a 不易喷射,而 R407C 和 R717(NH_3)存在优势。在使用制冷剂喷射时,应考虑轴承的自润滑,保证轴承的运转,考虑轴端的密封,防止润滑脂或润滑油进入压缩机腔[79]。

3 离心压缩机技术

离心压缩机是一种速度型压缩机,通过电机带动叶轮高速旋转,提高气体的速度使气体动能增加,通过扩压器使部分动能转化为压力能,从而提高气体的压力[80]。离心式热泵机组具有容量范围广、出水温度多样化、COP 高等特点[81]。

3.1 高效叶轮设计技术

高效节能的离心压缩机需要高效的离心式叶轮,目前国内外离心式叶轮均采用三元叶轮,气动性能好,叶轮效率高。常用的设计方法是基于 CFD 的设计方法,通过分析叶片参数对气动性能的影响实现离心式叶轮宽工况稳定高效的设计。

高效的叶轮设计及优化一般是反复迭代的过程,通过目标函数(如效率)获得较优结构。离心式叶轮使用分流叶片,可增加阻塞裕度,控制叶片载荷[82-83]。邵佳丰等[82]通过线性加权和法考虑分流叶片的周向位置与长度对性能影响,在分流叶片偏转角为 18°,长度为主叶片长度的 60%时,流量效率最高。对叶片厚度分布优化,在保证叶片强度的同时,减小尾迹损失;对叶片角度分布优化,可优化叶片载荷与速度分布,防止流动分离;对子午面优化,避免叶

片应力集中。随着计算机及人工智能的发展,不同结构参数的优化方法由多目标优化、遗传算法变为神经网络等计算精度高、推算清楚的算法[84-87]。

叶轮叶片的制造存在不确定性,导致几何出现偏差。通过测量,学者发现叶片弯度及厚度误差服从高斯分布,其中主叶片前缘附近的正厚度误差引起叶轮性能下降,减小叶片角度能够补偿上述引起的不利影响[88]。同样,叶轮在运行过程中仍存在不确定性,通过敏感度分析,获得性能更高、对边界不确定性灵敏度更低的叶轮[89-90]。

3.2 多级压缩、级间补气

两级压缩、级间补气使离心压缩机的压比更高、功耗降低,在高温热泵中应用广泛。补气型热泵较燃煤锅炉节省 15%以上的能量[91],较一般热泵系统增加一个闪蒸罐和副膨胀阀,如图 4 所示。通过级间闪蒸补气,可增大压缩机制热量,改善高压级的气动性能,提高整机 COP[92]。

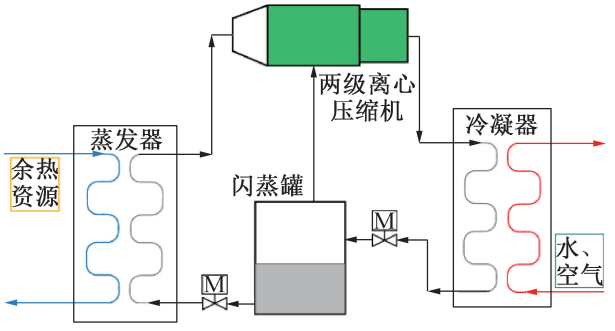


图 4 两级离心压缩机中间补气系统

Fig.4 Two-stage centrifugal compressor with vapor injection

两级离心式压缩机根据叶轮布置的不同及气路的差异有两种形式:串联式(同向)叶轮布置,结构简单紧凑;反向背对背布置,能够有效降低气体轴向力[93]。两种不同的离心式热泵产品如图 5 所示。

图 5(a)中的两级离心压缩机,叶轮背对背悬置于电机两侧,最大温升为 65 K,可制取 112 ℃热水/蒸汽,在蒸发温度为 55 ℃、冷凝温度为 115 ℃工况下制热量为 4 420 kW,制热 COP 为 4.29。图 5(b)为两个串联两级离心压缩机,4 级压缩,最大温升为 100 K,可制取 100~140 ℃热水/蒸汽,制热量为 3~10 MW。

W. Cousins 等[94]研究了单级补气离心压缩机的性能,当进行补气时,离心压缩机水头因子下降,补气量增加、补气孔增大均会使离心压缩机的 COP 增加。Hu Bin 等[95]对比了单循环双压缩机、双压缩机并联和双循环并联系统的性能,双循环并联比双压缩机并联系统 COP 提高 6.8%,且实验结果同样表明并联循环系统能够满足高温、大容量及高效率的要求[96]。另有学者研究喷液滴对离心压缩机性能的影响,液滴在压缩机中汽化吸热,带走压缩内部热量,但液滴量增加会使总静压比下降,功耗增加,压缩机空气动力学效率降低,应尽量避免运行过程中的液滴[97-98]。

(a) 叶轮反向布置

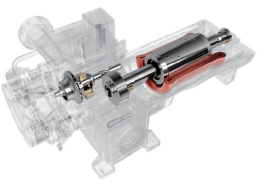
(b) 叶轮正向布置

图 5 离心式高温热泵产品

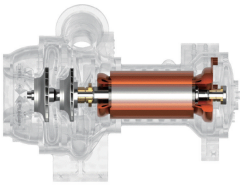
Fig.5 Centrifugal high temperature heat pump

3.3 高速永磁同步电机直驱

离心压缩机是速度型压缩机,其流量与转速为正比关系。离心压缩机驱动机构有齿轮增速机构[99]和高速永磁同步电机直驱机构,如图 6 所示。



(a) 齿轮增速结构



(b) 高速电机直驱结构

图 6 离心压缩机驱动机构

Fig.6 Driving mechanism of centrifugal compressor

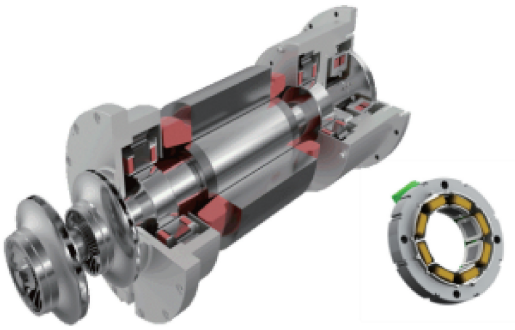
采用高速电机直驱叶轮,压缩机体积、质量为同冷量传统压缩机的 40%,机械损失降低 70%,运动件减少,振动噪声降低[100-101]。格力、美的、海尔、日立、荏原及冰轮等均推出了永磁同步直驱变频离心压缩机,能效提高的同时,满足制冷量及布置空间。

耐高温的高速电机是离心热泵的重要设备之一,其结构紧凑导致散热较差,降低电机的效率,影响压缩机和热泵系统性能。制冷或热泵系统中通常采用液体冷却和蒸发冷却,利用制冷剂或冷却液的潜热对电机进行冷却,但蒸发冷却会增加设备和系统的复杂度[102]。对于动压气浮离心式压缩机,系统高的冷凝压力可驱动液体冷却电机,冷却流道的进出口压差

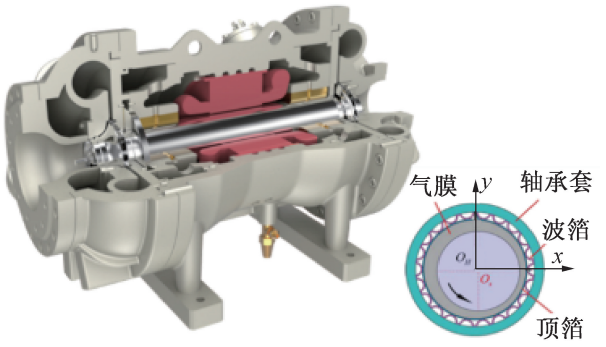
大,无需额外设备[103]。

3.4 无油轴承技术

磁悬浮轴承、气浮轴承等无油轴承可使离心压缩机实现高速无油运行,无摩擦,可提高压缩机效率[104]。无油轴承离心机的类型如图 7 所示。



(a) 磁悬浮离心机



(b) 动压气浮离心机

图 7 无油轴承离心机

Fig.7 Centrifugal compressor with oil-free bearings

磁悬浮轴承通过电磁力将压缩机轴悬浮,轴承控制器通过位移传感器对风压进行监控,改变转子轴向位置实现叶轮与蜗壳间隙的调整,有效调节风压[105]。磁悬浮离心机停机瞬间强烈气流冲击转子,使悬浮精度变差,甚至失稳。目前采用刚度阻尼抑制方法,主动抑制振动;使用干扰补偿方法,对系统所受扰动进行补偿,增加其抗干扰能力与鲁棒性[106-108]。

气浮轴承成本低、无需主动控制,但其承载力低,且制冷离心压缩机气体轴承的工作介质为制冷剂[109]。相对分子质量大的制冷剂减小止推轴承的承载力,但气膜厚度小时有较大静刚度[110]。轴承-转子系统的动力学研究是保证系统可靠运行的关键,应确保转子轴回转的径向误差不影响气膜厚度[111]。气浮轴承分为静压轴承与动压轴承,静压轴承的承载能力大于动压轴承,需要供气系统提供高压气体[93],制冷气浮离心压缩机多采用动压气浮轴承。海尔静压气浮离心压缩机的转动轴完全悬浮,与轴承无摩擦,降低机械损耗,大幅提高压缩机能效,综合能效比高达 12[112]。

4 高温热泵/蒸汽压缩机应用案例

4.1 热泵精馏

热泵精馏是把精馏塔塔顶蒸汽加压升温(或通过间接换热提取热量),使其热量用作塔底再沸器的热源,回收利用塔顶蒸汽的冷凝潜热,从而降低一次能源的消耗,达到节能降碳的目的。较传统精馏工艺,热泵精馏减少了塔顶冷却及塔釜加热的消耗,工艺流程如图 8 所示。

某石油炼化企业,采用精馏工艺,对原料液进行组分分离。原采用锅炉蒸汽作为再沸器热源,改造采用间接式热泵精馏流程,通过回收塔顶蒸汽热量,经热泵工质循环,在冷凝端输出高品位热量用于塔釜再沸。该热泵精馏系统采用喷油双螺杆压缩机,通过滑阀实现 15%~100%的容量调节,可实现年节省费用 1 460 万元,年减排 CO_2 79 530 t。

4.2 蒸汽制备

众多用热工业都需要高温蒸汽,同时冷却水、废水废热及乏汽等余热资源丰富,采用高温热泵/蒸汽压缩机可实现清洁高效的蒸汽制备。根据余热资源的不同,可采用高温热泵、闪蒸及蒸汽压缩等不同方式单独或组合实现。

某加工型企业,生产工艺需要大量 500 kPa 饱和蒸汽,目前采用外购高压蒸汽,减压至所需压力后使用,但外购蒸汽供应不稳定,且价格较为昂贵。厂区可利用热源包括稳定流量的污水源和制冷系统的冷凝热源,二者结合,采用三级串联制取 500 kPa 饱和蒸汽,系统如图 9 所示。该系统采用螺杆式水源热泵机组回收冷却水热量,吸收螺杆式氨热泵机组的冷凝热量,经由离心式蒸汽热泵机组及螺杆式水蒸气增压机组,得到工艺所需蒸汽,每小时蒸汽流量最大可达 7.4 t,大量减少外购蒸汽量,同时年节省费用 520 万元,年减排 CO_2 14 200 t。

5 结论

工业热泵高温压缩机面临高温升、大压比的技术挑战,需要应用低 GWP(Global Warming Potential)环保工质,妥善解决润滑油兼容性、电机与轴承冷却、转动部件热变形等技术难题,实现宽工况高效可靠运行。

对于螺杆式高温热泵压缩机,应开发专用的端面型线与螺杆转子结构,以获取更好的间隙密封特性、更高的单级压缩比和更大的吸排气面积;变频变容、两级压缩和中间补气技术的应用,可显著提高压缩机的全工况性能;高蒸发温度的压缩机应采用开启式结

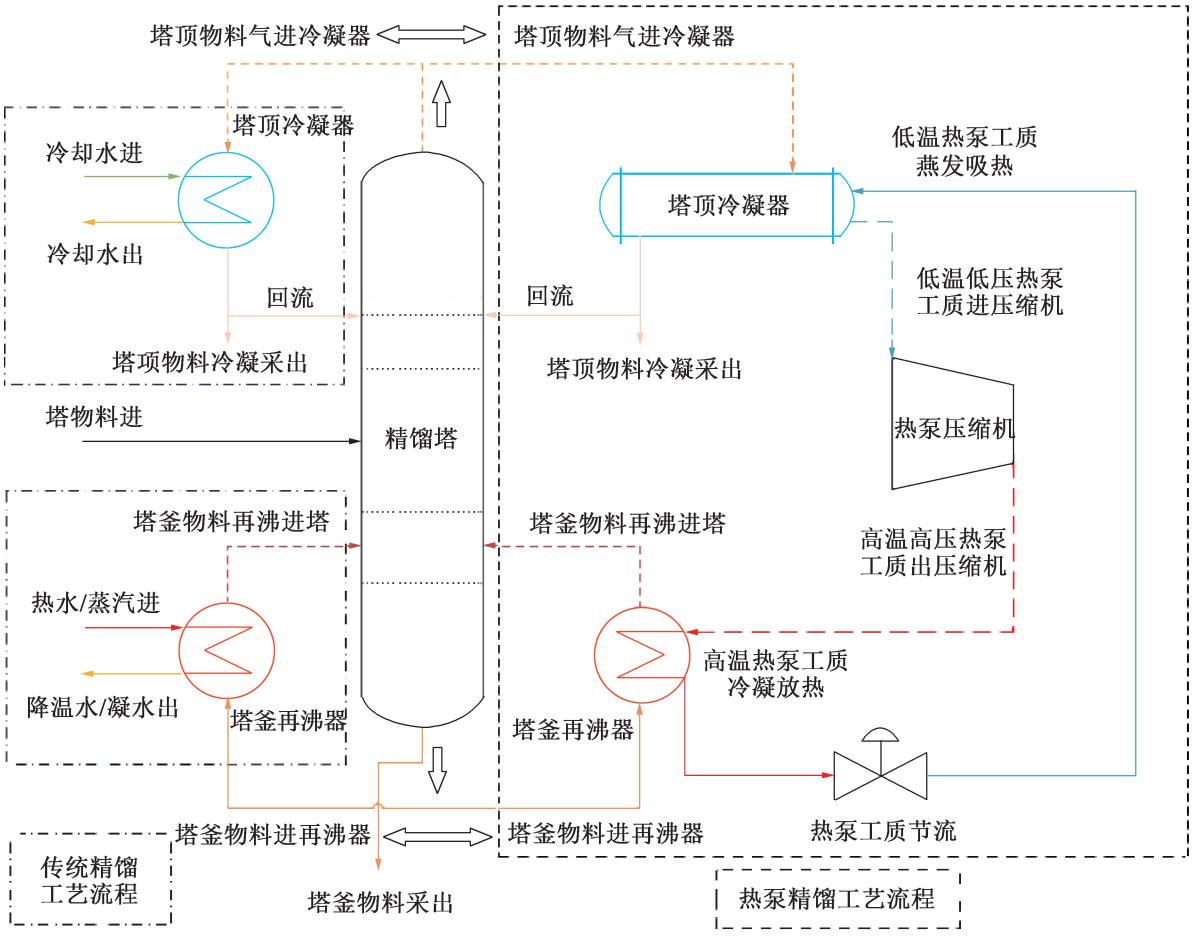


图 8 传统精馏与热泵精馏工艺流程

Fig.8 Traditional and heat pump distillation process flow

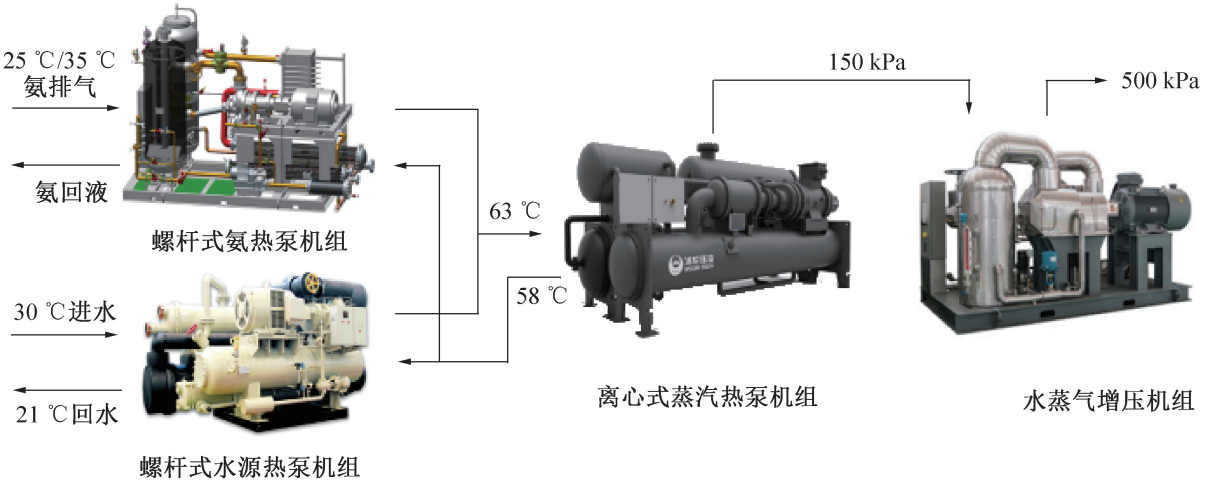


图 9 蒸汽制备流程

Fig.9 Steam preparation process flow

构,避免电机绕组温升超限;150 ℃以上冷凝温度的压缩机可考虑高速无油方案。

离心式高温热泵压缩机,应关注宽工况稳定高效气动设计,多采用 2~4 级压缩,高速永磁电机直驱可以提升压缩机效率,耐高温的电机与无油润滑轴承是离心式热泵压缩机向更高温区拓展的技术保障。

对于螺杆式水蒸气压缩机,应重点解决温升、轴端密封、转子热变形问题;已有喷水螺杆水蒸气压缩机单级饱和温升可达 60 K,两级压缩可以实现 75 K 饱和温升。

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