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ETHYLENE INDUSTRY

脱甲烷塔塔顶冷凝器甲烷出口线钢铝转换接头泄漏原因分析

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摘 要: 某石化公司裂解装置运行过程中,乙烯精馏塔塔顶甲烷含量持续上涨,经排查为脱甲烷塔冷凝器甲烷氢侧泄漏所致,更换新的钢铝接头后,甲烷含量逐渐下降满足生产要求。对运行状况进行分析,对接头开裂处样品进行宏观检查、金相分析、硬度检测和扫描电镜观察,开裂主要原因是日常开停工期间冷凝器升降温速率控制不当、钢铝转换接头存在制造缺陷等。通过制定严格升降温速率操作方案,严格细化和优化工艺操作,优化相应设备的操作规程,达到装置长周期平稳运行的目标。

关键词: 脱甲烷塔冷凝器 钢铝接头 爆炸焊 泄漏 原因分析

2024 年 4 月,某石化公司乙烯精馏塔塔顶甲烷含量持续上涨,经分析排查,判断脱甲烷塔塔顶冷凝器存在内漏。停工确认泄漏部位为脱甲烷塔塔顶冷凝器甲烷氢出口线钢铝转换接头上部的爆炸焊复合层发生开裂(见图 1)。

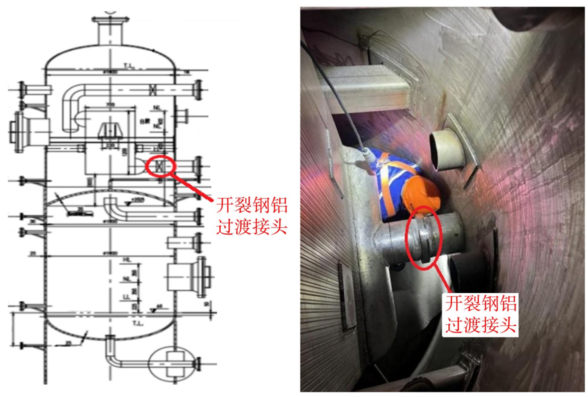

图 1 泄漏部位示意

1 调查与分析

1.1 设计、操作参数

脱甲烷塔冷凝器为内置铝制板翅式换热器,壳体设计压力 1.2/－0.05 MPa、设计温度－120/65 ℃,操作压力 0.025 MPa、操作温度－97.5 ℃;板翅通道设计压力 3.0 MPa、温度－120/65 ℃,操作压力 2.2 MPa、温度－98.5 ℃。设计通过－101 ℃的乙烯冷剂冷凝进料甲烷氢中的甲烷,为脱甲烷塔提供回流。本次泄漏是甲烷氢出口管道的钢铝接头,此处正常运行时操作压力 2.2 MPa,操作温度－100 ℃。

1.2 工艺操作情况

设备制造厂技术协议和 NB/T 47006—2019《铝制板翅式热交换器》规范中要求“升降温不得超过 30 ℃/h 和升降温速率不得大于 1 ℃/min”。经排查,脱甲烷塔冷凝器升降温高于 30 ℃/h 的共有 11 次,温度变化对钢铝接头开裂存在影响。

1.3 钢铝接头检修

从钢铝接头投用至开裂失效期间进行过 1 次停工检修。检修期间对钢铝接头进行无损检测无异常,冷凝器内部芯体支架和耳式支座的 4 个连接螺栓处于自由态(可自由伸缩,满足技术要求),检查结果均符合要求。

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2　检验、检测与试验分析

从脱甲烷塔冷凝器现场割取泄漏钢铝转换接头进行宏观检查、成分分析、金相组织分析、显微硬度测试、SEM 微观形貌分析及 EDS 能谱分析。

2.1　宏观检查

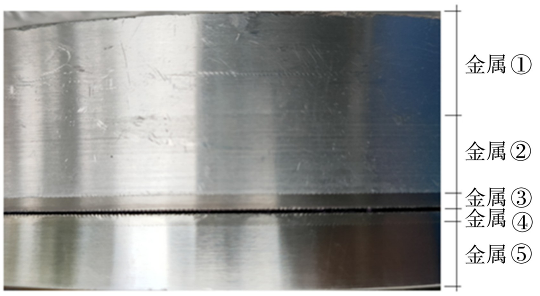
2.1.1　开裂情况

对钢铝转换接头整体和泄漏部位进行宏观检查，失效钢铝转换接头上部爆炸焊复合层开裂缝隙宽约 0.5 mm，开裂长度约为接头法兰周长 1/4，转换接头整体及各成型复合层未见异常变形，表面未见腐蚀特征，初步判断钢铝接头复合层开裂为脆性断裂（见图 2）。

图 2　钢铝接头复合层开裂情况

2.1.2　尺寸检查

宏观检查发现共 5 层金属结构，依据资料和实际情况确认各层金属材料和厚度，见图 3。



金属① 5083 铝镁合金（与系统管道一致），厚 14.5 mm；金属② Al，厚 11.0 mm；金属③ Ti，厚 2.0 mm；金属④ Ni，厚 1.5 mm；金属⑤ S30408（与系统管道 304L 一致）厚 8.0 mm

图 3　钢铝接头各层金属材料与厚度

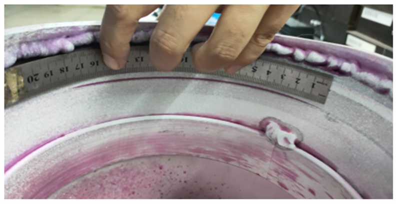
2.1.3　焊接接头检查

接头两侧钢、铝管道对接焊缝焊接质量较差，与不锈钢管道、铝合金管道焊缝组对间隙较大，焊缝焊接时摆动较宽，如此焊接操作会造成更大的管道轴向收缩应力、环向拉应力和附加弯矩。而该钢铝接头复合层开裂位于甲烷出口水平管道上部，表明安装时焊接操作产生的应力对钢铝接头的开裂产生了影响。

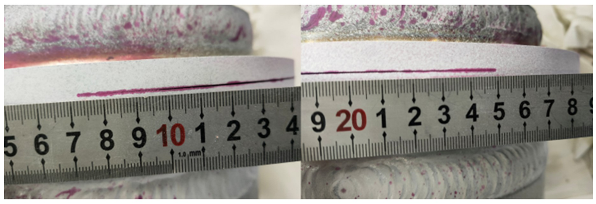
2.1.4　钢铝接头复合层开裂检查

对钢铝接头复合层进行渗透检测、超声检测和宏观检验，确认复合层开裂的部位、尺寸和开裂断口特征。

1）渗透检测。渗透检测发现接头内表面开裂 180 mm（－75 ~ ＋105），外表面开裂 178 mm（－70 ~ ＋108），见图 4。开裂位于金属③－金属④结合界面，开裂形状为内长外短，说明接头复合层开裂由内部向外部界面开裂。



内表面



外表面

图 4　钢铝接头渗透检测

2）超声检测。发现 1 处分层区域，分层位于金属结合界面，分层区域以接头外圆弧面测量，开裂弧长 210 mm（－80 ~ ＋130）。

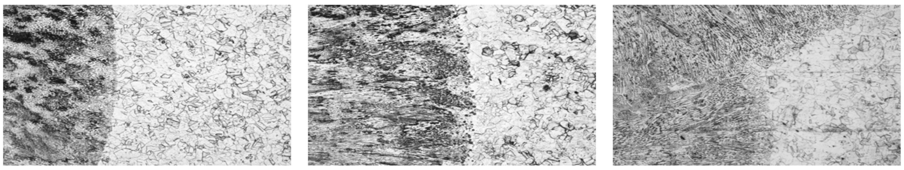
3）断裂界面宏观形貌检查。断面呈典型的爆炸焊接断面特征，断开界面整体较为干净，开裂呈整体脆性开裂特征。

2.2　金相检测

对钢铝爆炸焊复合接头 3 点、6 点及 12 点方向不锈钢侧管道焊接接头金相试样进行检测，其母材金相组织均为奥氏体及孪晶，焊缝金相组织为奥氏体基体及枝晶状分布的高温铁素体，熔合线组织细密。焊缝组织形态因焊接热输入情况有所差别，但均未发现明显异常组织（见图 5）。

对钢铝爆炸焊复合接头 3 点方向、6 点方向及 12 点方向铝侧法兰焊接接头金相试样的检查表明，其母材金相组织均为铝基及固溶体、焊缝金相

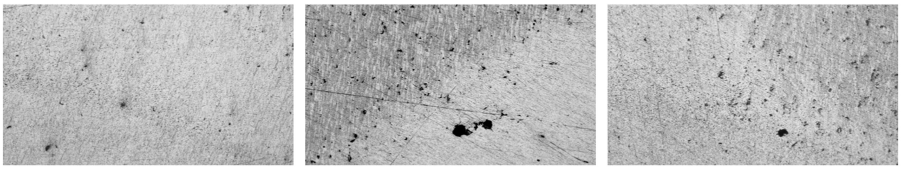
组织为铝基体,枝晶状分布,熔合线组织细密。未发现明显异常组织(见图6)。



3点方向　　6点方向　　12点方向

(焊缝中:熔合线 100×)

图 5　不锈钢侧焊接接头金相检测



3点方向　　6点方向　　12点方向

(焊缝中:熔合线 100×)

图 6　铝侧焊接接头金相检测

2.3　硬度检测

采用 XHV－1000 型全自动显微维氏硬度计开展爆炸焊复合接头各层复合界面及 Ti、Ni 的硬度测试,结果见表 1～4。

表 1　钢铝爆炸焊复合接头不锈钢侧管道焊接接头硬度检测　　HV

测量部位	测试条件	第一次	第二次	第三次	平均值
3 点方向母材	HV10/10	187.5	165.7	181.9	178.4
3 点方向焊缝		167.6	166.5	174.4	169.5
6 点方向母材		178.5	179.9	178.7	179.0
6 点方向焊缝		170.6	167.3	174.3	170.7
12 点方向母材		179.3	179.3	182.9	180.5
12 点方向焊缝		172.0	178.7	191.5	180.7

表 2　钢铝爆炸焊复合接头铝侧法兰焊接接头硬度检测　　HV

测量部位	测试条件	第一次	第二次	第三次	平均值
3 点方向母材	HV10/10	72.5	76.7	75.6	74.9
3 点方向焊缝		71.3	73.5	72.4	72.4
6 点方向母材		74.8	80.5	79.0	78.1
6 点方向焊缝		77.4	76.3	77.0	76.9
12 点方向母材		77.4	79.1	77.0	77.8
12 点方向焊缝		74.4	73.2	73.0	73.5

表 3　3 点方向钢铝爆炸焊接头复合界面硬度检测　　HV

测量部位	测试条件	第一次	第二次	第三次	平均值
爆炸复合界面 S30408 基层	HV10/10	258.7	264.9	236.4	253.3
爆炸复合界面 S30408－Ni 界面	HV1/15	263.2(S30408 侧)	224.3(Ni 涡)	275.8(S30408 涡)	254.4
爆炸复合界面 Ni 基层	HV1/15	184.3	191.7	192.1	189.4
爆炸复合界面 Ni－Ti 界面	HV1/15	223.7(Ni 涡)	222.7(后涡)	231.5(Ti 涡)	226.0
爆炸复合界面 Ti 基层	HV1/15	169.6	168.6	177.8	172.0
爆炸复合界面 Ti－Al 界面	HV1/15	90.53(前涡)	80.13(前涡)	74.40(后涡)	81.70

表 3(续)　　HV

测量部位	测试条件	第一次	第二次	第三次	平均值
爆炸复合界面 Al 基层	HV10/10	42.1	48.2	41.5	43.9
爆炸复合界面 Al－5083 界面	HV1/15	80.00(后涡)	69.64(前涡)	76.02(交界)	75.20
爆炸复合界面 5083 基层	HV10/10	87.8	91.7	86.2	88.6

表 4　6 点方向钢铝爆炸焊接头复合界面硬度检测　　HV

测量部位	测试条件	第一次	第二次	第三次	平均值
爆炸复合界面 S30408 基层	HV10/10	239.7	240.4	270.0	250.0
爆炸复合界面 S30408－Ni 界面	HV1/15	277.1(Ni 涡)	311.3(交界)	316.4(后涡)	301.6
爆炸复合界面 Ni 基层	HV1/15	193.4	209.1	207.4	203.3
爆炸复合界面 Ni－Ti 界面	HV1/15	239.5(Ni 涡)	246.8(Ti 涡)	242.2(后涡)	242.8
爆炸复合界面 Ti 基层	HV1/15	181.2	187.1	175.5	181.3
爆炸复合界面 Ti－Al 界面	HV1/15	77.00(Al 涡)	80.27(前涡)	87.37(Ti 涡)	81.50
爆炸复合界面 Al 基层	HV10/10	41.5	43.0	45.4	43.3
爆炸复合界面 Al－5083 界面	HV1/15	70.55(5083 侧)	65.90(Al 侧)	59.49(交界)	65.30
爆炸复合界面 5083 基层	HV10/10	87.7	88.9	81.7	86.1

硬度试验结果表明:钢铝爆炸焊复合接头不锈钢侧管道焊接接头母材与焊缝硬度测试值无明显异常,但焊缝区硬度分布不均匀,且 12 点方向焊缝硬度平均值高于其它部位。钢铝爆炸焊复合接头铝侧法兰焊接接头硬度测试值无明显异常。爆炸复合界面硬度检测的各基层材料内硬度较为均匀。

2.4　扫描电镜观察与能谱分析

2.4.1　扫描电镜观察

钢铝接头 Ni 材与 Ti 材爆炸复合区爆炸焊波形波长约为 0.7 mm,电镜高倍下可见爆炸复合漩涡中层流、湍流组织形态(见图 7);后漩涡 0.14 mm 范围内存在气孔、夹杂、空隙、裂纹等缺陷(见图 8),后漩涡中有 1 条贯穿夹杂、空隙的裂纹,长约 0.063 mm,Ni、Ti 金属间化合物层流结晶组织形态明显,湍流组织区出现较多的气孔、夹杂、空隙、裂纹等缺陷,Ti 材侧与 Ni、Ti 金属间化合物的焊接界面明显(见图 9)。另一处波形的后漩涡,层流、湍流组织形态明显,在湍流与 Ni 材的结合区有 1 条贯穿空隙长约 0.12 mm 的裂纹(见图 10)。

对该试样其它波形进行电镜高倍观察,发现每个波形后漩涡均存在裂纹、气孔、夹杂、空隙等缺陷,均出现在 Ni、Ti 金属间化合物湍流组织边缘的结合区,且易出现开裂裂纹。在长期运行使用中,爆炸焊复合区的微小缺欠包括漩涡的层流、湍流组织、扩展开裂形成结合强度最薄弱的区域。

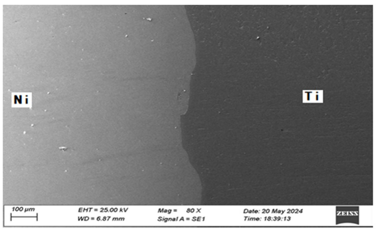


图 7　Ni－Ti 爆炸复合区的爆炸焊波形

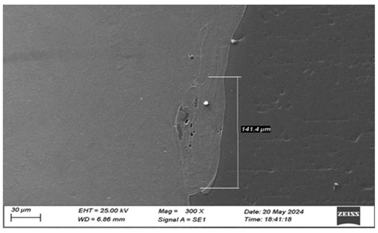


图 8　波形漩涡形貌

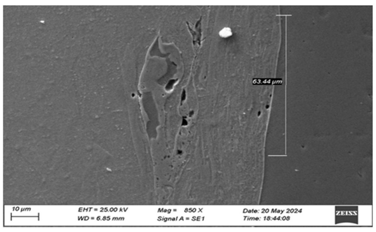


图 9　漩涡中夹杂、空隙、裂纹及流态组织形貌

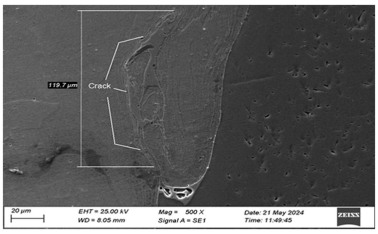


图 10　漩涡金属流态组织形态和裂纹

2.4.2　能谱分析

1）对钢铝接头复合层进行线扫描，见图 11。图 11 从左向右依次是 CrNi 不锈钢、Ni 材、Ti 材、Al 材，与接头制造厂家提供的资料一致。

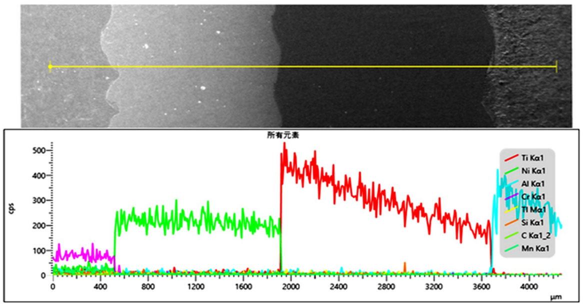


图 11　钢铝接头复合层金属成分线扫描

2）对开裂界面的瞬断区条纹波浪的波峰和波谷处进行能谱检测。

图 12 中 Ni 材侧复合区断裂后露出断续 Ti 材，Ti 材断裂处呈现密集韧窝状塑性断口特征（图中 25、26、29、30 部位），Ti 材断裂处主要元素均为 Ti、C，未撕裂的 Ni 材侧主要元素为 Ni、Ti、C，表明 Ni、Ti 材料开裂界面是沿基板和复板强度较弱的 Ni 材侧的爆炸焊复合区开裂。

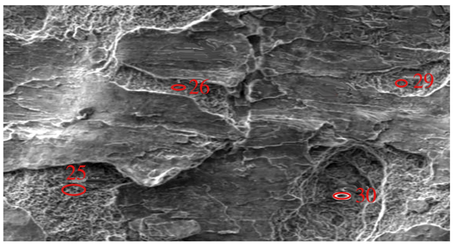


图 12　开裂界面瞬断区条纹波浪能谱检测

3　分析结论

脱甲烷塔塔顶冷凝器甲烷出口线钢铝转换接头开裂原因是：钢铝接头制造时 Ni－Ti 爆炸焊工艺参数偏大导致复合区产生过多液体金属形成气孔、夹杂、空隙、裂纹和脆性组织等微小缺欠，在长期运行使用中，Ni－Ti 爆炸焊复合区微小缺欠逐渐扩展开裂连接形成复合区结合强度最薄弱部位，此外钢铝转换接头除在运行时受到内外压力、各类重力、支撑反作用力、连接管道和其它部件的作用力影响，还受到多次开停工温度梯度或热膨胀量不同引起的作用力以及压力波动冲击载荷等复合应力的影响，当管系轴向拉应力超过Ni－Ti接头复合区最薄弱处的承载强度时，转换接头发生脆性开裂。

4　结语

1）使用单位应严格按照 NB/T 47006—2019《铝制板翅式热交换器》中的要求，“升降温速率不得大于 1 ℃/min，升降温速度不得超过 30 ℃/h”进行升降温操作。应严格细化和优化工艺操作，优化相应设备的操作规程，避免系统工艺波动带来的冲击。

2）钢铝转换接头两侧管道的焊接接头应采用多段多层多道焊对称焊接方式，转换接头所在管道的所有焊口焊接安装时采用降低管道轴向焊接应力的焊接顺序原则：先焊轴向自由收缩应力最大且金属材料热膨胀系数最大的焊缝，最后焊接固定焊口。严格控制焊接组对尺寸，防止坡口组对尺寸过大造成焊材填充多和焊接热输入量过大形成较大的焊缝收缩应力。焊接工艺尽可能选择较小的热输入能量，控制各接头的焊接顺序和管系安装应力，并按钢铝接头上的温度显示色标控制，且焊缝道间温度不大于 150 ℃。

3）建议在冷凝器出口线位置增设测温仪表，监测干燥、开车、停车和瞬时操作条件温度变化对冷凝器各部件的影响。

4）建议在爆炸焊钢铝转换接头投用前采用渗透、超声检测增加对爆炸成形焊接接头复合层缺陷检测，发现问题及时更换。在装置检修窗口期安排对此类爆炸焊焊接接头进行渗透、超声无损检测，确保异种金属接头的制造质量能够满足安全使用的要求。对爆炸焊钢铝转换接头进行日常维护保管，洁净储存防止沾染污物。

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CAUSE ANALYSIS AND MEASURES AGAINST ETHYLENE LOSS IN METHANE TAIL GAS FROM ETHYLENE PLANTS [1]

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Abstract: The methane tail gas generated within ethylene plants is typically utilized as regeneration gas and fuel for cracking furnaces. During the cryogenic separation process, excessive ethylene is lost to the tail gas, resulting in a high concentration of olefins in the tail gas, which will have adverse effects on the economy and the long-term safe and stable operation of the plant. Based on the Front-End Depropanizer and C_2 hydrogenation of Sinopec LECT technology, this paper analyzes that the separation efficiency of C_1 and C_2 in the high-pressure demethanizer system is the primary cause of the olefin concentration fluctuations in methane tail gas. By analyzing the influence of low methane/hydrogen ratio in the cracked gas composition on the separation efficiency of high-pressure demethanizer system, this study explores the measures for enhancing the heat exchange efficiency of the overhead condenser and controlling the amount of ethylene in the methane tail gas by optimizing the operating conditions and locally reconstructing the processes while maintaining the primary separation process unchanged. These measures include adjusting the operating conditions of the demethanizer system, increasing the circulation of methane, and recovering ethylene from tail gas. Additionally, the study compares the impact of various schemes on plant investment and operational energy consumption levels, and establishes several methods for controlling the ethylene concentration in the demethanizer system and the methane tail gas.

Key words: cryogenic system; demethanizer; methane/hydrogen ratio; expander/recompressor; ethylene loss rate; regeneration gas

CONTROL AND OPTIMIZATION OF WATER CONTENT IN NMP SOLVENT DURING OPERATION OF BUTADIENE UNITS [7]

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Abstract: The 35 kt/a butadiene unit of a petrochemical company uses N-methylpyrrolidone as the extraction solvent. In the NMP method for butadiene production, the control of water content in NMP plays a crucial role in the normal production of the unit. Excessive water content can easily cause poor solvent selection performance, insufficient heat source in the solvent system, and fluctuations in pressure difference in the main washing tower. This article summarizes the experience in controlling the water content in NMP solvent of the butadiene unit.

Key words: butadiene; NMP solvent; water content

CAUSE ANALYSIS AND SOLUTIONS TO INCREASED PRESSURE DIFFERENCE IN GASOLINE FRACTIONATORS [10]

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Abstract: Since the ethylene plant of a refinery was put into operation in June 2018 after overhaul, the pressure difference in the gasoline/diesel section of gasoline fractionator has gradually increased from 5.4 kPa at the initial startup to a maximum of 7.5 kPa, while the pressure difference in the pumparound section and the quench oil section remained relatively stable. In response to the increased pressure difference in the gasoline/diesel section of gasoline fractionator, relevant measures were developed to control the rising trend and stabilize the pressure difference within 6 kPa. The internal components of the tower were modified during the overhaul in 2023, successfully reducing the pressure difference to around 2.5 kPa.

Key words: gasoline fractionator; fouling; pressure difference; operation optimization; technical improvement

CAUSE ANALYSIS OF LEAKAGE AT STEEL-ALUMINUM TRANSITION JOINT OF METHANE OUTLET LINE OF OVERHEAD CONDENSER IN DEMETHANIZER [15]

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Abstract: During the operation of the ethylene cracking unit of a refining and chemical plant, the methane content at the top of the ethylene distillation column continuously increased. The investigation and analysis showed that it was caused by the leakage on the methane-hydrogen side of the condenser in demethanizer. After replacing the steel-aluminum transition joint with a new one, the methane content gradually decreased, meeting the production requirements. Through the operational analysis and the macro inspection, metallographic analysis, hardness testing and scanning electron microscope observations of the failed samples, it was found that the main reasons for the cracks include the improper control of the cooling and heating rates of cold box system during daily start-up and shutdown and the manufacturing defects in the steel-aluminum transition joint. By formulating strict operating procedures for cooling and heating rates, strictly refining and optimizing process operations, and optimizing the operating procedures for relevant equipment, the goal of long-term stable operation of the unit can be achieved.

Key words: demethanizer condenser, steel-aluminum joint; explosion welding; leakage; cause analysis

APPLICATION OF SPIRAL WOUND TUBE HEAT EXCHANGERS IN PROPANE DEHYDROGENATION PROCESS [20]

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Abstract: This paper discusses the application of spiral wound tube heat exchangers in propane dehydrogenation process. The problems of traditional tubular heat exchangers in propane dehydrogenation process are analyzed, and the structure, working principle and characteristics of spiral wound tube heat exchangers, including high efficiency, compactness and multi-media heat exchange capacity, are expounded. Through the comparison with traditional tubular heat exchangers and the actual case analysis, the advantages of spiral wound tube heat exchangers in improving heat exchange efficiency, reducing energy consumption and carbon emissions, and improving propylene yield are demonstrated. At the same time, the application cases and process parameters of spiral wound tube heat exchangers in propane dehydrogenation process are elaborated in detail.

Key words: spiral wound tube heat exchanger; propane dehydrogenation process; heat exchange efficiency; energy consumption and carbon emissions; propylene yield

EXPLORATION AND PRACTICE OF "5-YEAR OVERHAUL" FOR CRACKING GAS COMPRESSORS IN ETHYLENE PLANTS [23]

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Abstract: Cracking gas compressor is a critical unit in ethylene plants. The unplanned shutdown of cracking gas compressor due to operational failure will cause incalculable losses to the production of ethylene plants. Therefore, the good operation of cracking gas compressor is crucial for the smooth production of ethylene plants. With the extension of operating time of the cracking gas compressor unit of a company, problems emerged in various components of the compressor unit. The problems of cracking gas compressors found during the overhaul, including the serious wear of water injection nozzles, the coking in cylinder body and flow passages, and the corrosion of shaft seal gas seal, were tackled and eliminated one by one, ensuring that the "5-year overhaul" target of cracking gas compressors can be met.

Key words: ethylene plant; cracking gas compressor; problem tackling and elimination

CAUSE ANALYSIS AND SOLUTIONS TO MALFUNCTION OF TURNING GEAR OF CRACKING GAS COMPRESSORS [27]

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Abstract: Turning gear is a safety protection device for cracking gas compressor unit. During the single test of the steam turbine of a cracking gas compressor unit of an ethylene plant, the turning gear was operated normally. When the compressor unit was turned up after the combination of steam turbine and compressor through the coupling, the turning gear shook back and forth, and the compressor rotor could not rotate normally. The turning gear could not meet the turning requirements of the compressor unit. In this paper, the problems in the starting process of the turning gear of cracking gas compressor unit in ethylene plant are analyzed in depth, and a corresponding solution is put forward. By lowering the rotating speed and increasing the starting torque, the normal operation of the turning gear of compressor unit can be ensured.

Key words: steam turbine; turning gear; torque; malfunction; solution

CAUSE ANALYSIS AND TREATMENT METHODS FOR MECHANICAL SEAL LEAKAGE OF BUTADIENE TWIN SCREW COMPRESSORS [30]

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Abstract: The butadiene twin screw compressor of a petrochemical company is a critical unit that directly affects the safe and stable production of the unit. During previous maintenance processes, the seal on the compressor's outlet side has leaked multiple times. After the maintenance in July 2024, the leakage rate of the seal on the compressor's outlet side was approximately 48 L/h, far exceeding the allowable leakage standard for mechanical seal (0.02 L/h). Due to