天然气增压站经济优化:管道与增压站选型

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摘　要:对于外输管道的天然气增压站,其全周期运行经济性很大程度上取决于压缩机组的运行情况。讨论了管道和增压站选型的部分概念,如利用管道水力学优化管线上增压站的数量及增压站中压缩机组数量等。这些设计原理应在燃料消耗、维护及大修等设计标准上予以考虑。结合每个增压站和每个系统中机组数量的考虑,对增压站与系统的可用率进行了探讨。

关键词:天然气增压站;管道水力学;增压站;优化;可用率

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1　Pipeline Sizing Considerations

管线选型考虑

Kurz and Ohanian[1] evaluated different options for pipe diameters, pressure ratings and station spacing for a long distance pipeline. A 3 220 km(2 000 mile) onshore buried gas transmission pipeline for transporting natural gas with a gravity of 0. 6 was assumed(Figure 1).

Kurz R 和 Ohanian S[1] 评估了对于长距离管线,管道直径、压力等级与站场间距的不同选择。本文假定一条 3 220 km(2 000 mile)的陆上埋地天然气输送管线,输送气体密度为 0. 6(图 1)。

Assuming that pipes will be available in2" diameter increments from pipe mills, the nearest even increments of the above-mentioned theoretical diameters were selected (24", 28", and 34" for 152 bar, 103 bar and 69 bar (1 bar = 0. 1 MPa) pressures respectively) and analyzed by varying the number of stations along the pipeline. The result of this refinement is shown in Figure 1, where present value is plotted against number of stations for each pressure level. The minima for each are shown in the chart with present value, total horsepower, and number of stations. In this study, the 69 bar pipeline has the lowest present value, thus would be the most cost effective solution.

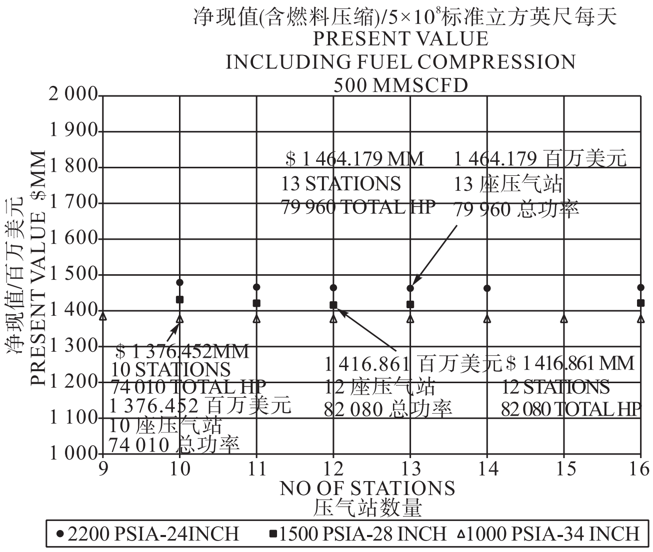

Figure 1:Optimum number of stations and optimum maximum operating pressure (MAOP) for the 3 220 km (2 000mile), 560 000 Nm^3/h sample pipeline. The lowest cost configurations for each MAOP solution are marked(from[1]).

图 1　一条长 3 220 km(2 000 mile)、输量为 560 000 Nm^3/h 管线的最优压气站数量与最优的最大允许操作压力(MAOP)。标记了每种运行压力下最低成本的压气站配置[1]。

假定来自制管厂的钢管直径以 2"的间隔增加,选择

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24”、28”与 34”及其分别对应压力 152、103 与 69 bar(1 bar = 0. 1 MPa)的 3 条管线,对沿线不同的布站数量进行分析。这样细化研究的结果见图 1,图 1 中绘制了不同压力等级下布站数量对应的净现值。每种情况的折合净现值如图 1 所示,图上反映了投资、总装机功率、压气站数量。该案列说明,69 bar 管线的净现值最低,因此是最经济的解决方案。

In actual practice, for commonality reasons, identical size units will be installed in the stations. In order to have identical power at each station, the station spacing will be adjusted(dependent on the geography) since the stations at the beginning of the line will consume more power than the stations at the end of the line due to the power required for fuel compression. Identical power at each location also depends on site elevation and design ambient temperature, which would define the site available power from a certain engine.

在实际应用中,为了保持机组的统一,同一站内应安装相同的机组。为了保持各站有相同的功率需求,需要根据地形调整站间距,由于沿途各站存在自耗气,下游的输气总量小于首站及管道上游各站,因此管线首站比管线末站消耗更多的压缩功。为保持相同功率而选择的站址也受海拔与设计环境温度影响,因为这些因素决定燃机的实际现场出力。

One of the key findings is, that the optimum is relatively flat in all cases. This meansin particular, that certain considerations may favor larger station spacing, with higher station pressure ratios, and higher MAOP in situations where pipelines are routed through largely unpopulated areas.

其中一个重要发现是,最优方案对于其它方案来说其优势并不特别突出。这就意味着若管线穿过人烟稀少的地区则可以考虑增大站间距,提高站的压比与 MAOP(最大允许操作压力)。

2 Typical Application 典例应用

For a case study we consider an international long distance pipeline. The total length of the line is about 7 000 km. The pipeline consists of two 42” parallel lines which turn into single a 48”line at the crossing of an international border. The pipeline design throughput is 30 billion Nm^3 per year and maximum operating pressure of this pipeline is 9. 8 MPa. There are 10 compressor stations planned in one area, and over 20 stations in the receiving country. After first gas, it takes 5 years to build up to full capacity.

在案例研究中我们评估了一条跨国长输管线,线路总长度为 7 000 km。管线由 2 根 42”并行管线组成,在跨越国境边界合并为 1 根 48”管线。管线设计输送能力 300×10^8 m^3/a,最大运行压力 9. 8 MPa。在一个区域中设置 10 座压气站,在接气国家设置约 20 多座站场。投产后,预计 5 年达到管线设计输送能力。

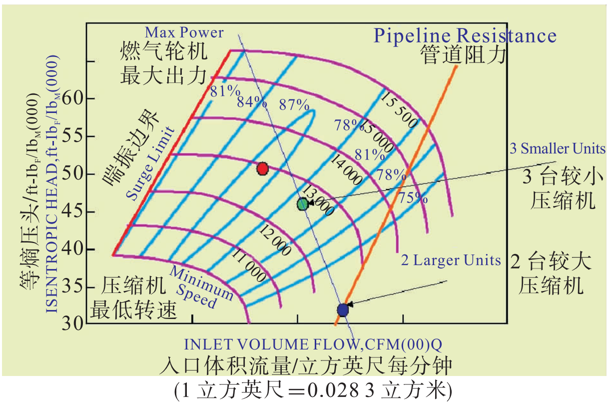

Figure 2:Impact of loss of one unit forthe 3 unit and the 2 unit scenarios

图 2 对比 3 台压缩机组与 2 台压缩机组其中 1 台机组失效的影响

When we compare operations of the compressor station we need to recognize two main approaches. We can either operate with fewer of larger turbocompressor units(Case A, 2 large units) or with a higher quantity of smaller turbocompressor units(Case B, 3 small units). The following factors need to be considered when selection of either option is decided. In evaluating the system reliability and maximum throughput the impact of unit outages needs to be considered. If we were to consider two large 30 MW units the failure of one of them will result in 50 % reduction of power available whereas if we consider 3 smaller 20 MW units the failure of one of them will result in only 33 % power reduction. Figure 2 outlines the basic fact that, if the surviving units run at full load to make up as much flow as possible, the operating point for the Case B will be close to the highest efficiency island so the remaining on-line compressors will be working more effectively compared to the Case A when the single remaining large unit will be working in the stonewall area. It is obvious, that pipeline recovery time will be shorter in case B.

比较压气站运行方案时我们需要认识到两种重要方法。既可以运行数量较少但功率较大的透平压缩机组(案例 A,2 台大机组),也可运行功率较小但数量较多的透平压缩机组(案例 B,3 台小机组)。比选这两种方案时,需考虑如下因素。在评估系统的可靠性与最大输送能力时,需考虑机组失效所造成的影响。如果考虑 2

台 30 MW 机组,其中 1 台机组失效,将导致可用功率减少 50 %;然而如果考虑 3 台 20 MW 机组,其中 1 台机组失效,将仅导致可用功率减少 33 %。图 2 说明如果 1 台机组失效后,剩下的机组会尽可能满负荷运行来保证输气量,案例 B 中的压缩机工作点将靠近高效区,而案例 A 中剩下的压缩机将会运行在阻塞区附近。显然,案例 B 的管线恢复时间更短。

Based on an analysis by Santos [2-3], Case A can represent even more problems. The amount of gas that the single remaining 30 MW unit will have to process is so big that it will put this remaining unit into choke, and thus for practical purposes out of operation. The amount of fuel that the remaining unit is going to burn will not justify that negligible increase in head that this unit will provide. So, practically, when one larger turbocompressor will be out of operation, the second will have to be shutdown and the station will be bypassed. Station configurations with the single oversize driver and either no standby or standby on each second or third station are often advocated. The arguments in favor of this method are very high pipeline availability (99.5 %) and high efficiency (40 % ~ 42 %) of the larger 30MW turbocompressor units. In fact, designing for a turbine oversized by 15 % will lead to normal operations at part load conditions almost all the time (99.5 %) where there will be negative impact on turbine efficiency and, as a result of it, increased fuel consumption. Another negative impact of this approach is that normally this pipeline would operate at lower than MAOP pressure, whereas the highest operational pipeline pressure produces less pressure losses and, therefore, lower requirements for the recompression power. The reason for that is the maintenance schedule for the turbocompressors on the stations with the single units without standby. In order to perform maintenance on these units the pipeline, linepack will have to be maximized up to MAOP, so that unit can be taken off line and the pipeline throughput will not be impacted. Therefore, the normal pipeline operations have to be based on a lower MAOP. Also worth mentioning is the pipeline capacity when considering the single turbocompressor approach. Many pipelines transport gas owned and produced by different commercial entities. As such the gas fields development time and gas availability depends on many technological and, lately, political factors that may potentially have negative impact on pipeline predicted capacity growth. In these conditions the single oversized turbocompressor will be either working into deep recycling mode until the expected amount of gas will become available or start operation with smaller capacity compressor stages which will subsequently require a costly change of the internal bundle.

根据 Santos S P[2-3]的分析,案例 A 可能带来更多问题。由于剩下 1 台 30 MW 机组需要处理的气量太多导致机组出现拥塞,因此实际上不能正常运行。剩下机组消耗的燃料气很多但却只能提供微小能头的增加。所以实际上,当 1 台较大的透平压缩机失效后,第 2 台机组将不得不停机,气体只能越站输送。通常情况下一般提倡压气站配置较大的驱动机(功率备用)且无备用机组,或配置合适功率的驱动机,在其后第 2 或第 3 个站场考虑备用机组。支持这种配置的理论是,管线有非常高的可用率(99.5 %)及 30 MW 大机组较高的效率(40 % ~ 42 %)。实际上,透平设计超出正常功率 15 % 的裕量就会使得燃机在几乎所有(99.5 %)运行时间内一直处在部分负荷状态下,这不仅会影响透平的效率,还会增加燃料气消耗。该方法的另一负面影响在于,这种配置还会使管线的运行压力一直低于 MAOP,我们知道管线的运行压力越高,产生的压损越小,再增压需要的功率也越小。导致这个问题的原因是无备用的单机组的维护无法得到保证。为了对管线上的这些机组进行维修,需要使管道储气量在最高运行压力下达到最高,然后才能停下机组,这样管线的输送能力才不会受到影响。因此,通常情况下管线都在低于 MAOP 工况下运行。同样值得一提的是单台透平压缩机组方案时管道的输送能力。许多管线输送的天然气分别由不同单位生产以及拥有,这些气田的开发时间进度与天然气的外输量由许多技术的、政治的因素决定,这些因素很可能对管线远期达到设计输量的能力产生负面影响。在这些情况下,单台较大透平压缩机要么会一直打循环运行直到达到预期输气量,要么开始时安装一个处理低流量工况的压缩机机芯,但是随后换大流量机芯又会增加投资成本。

3 Fuel Comparison 燃料比较

It is increasingly important to evaluate all seasons conditions when making a comparison between two different station layout cases. For the subject pipeline different design organization were involved in the pipeline feasibility study. One of them has used summer conditions only and came to the conclusion that larger turbines are preferred option. Another source used annual average conditions and came to the opposite conclusion. The reason for that was the fact that during winter, fall, and spring months, which cover total of 9 out of 12 months of operation, one of the smaller turbcompressors was put in the standby mode. Due to lower ambient temperature the amount of power available from the remaining 2 units was enough to cover the 100 % duties due to high compressor efficiency. This was not true for the Case 1(based on same explanation above) and both 30 MW units had to work in the deep part load with unsatisfactory turbine efficiency. The fact that operational mode became 2 + 2 for Case B gave additional benefits worth mentioning. Since two turbocompressors were in standby mode there was an opportunity to do all maintenance work during this time of the year. It means that availability of this system becomes superior compare to Case A, especially if we were to consider summer months of operations.

比较两种不同站场布置案例时，评估所有季节的工况越来越重要。之前所述的管道项目有不同的机构参与了前期的管道可行性研究。其中一个机构仅考虑了夏季工况，然后就得出结论认为大机组更优。另一个组织则考虑了年平均工况从而得出了相反的结论。其原因在于，冬季、秋季与春季在 1 年中共占了 9 个月，这段时间内其中较小机组中的 1 台则处于备用状态。当环境温度较低时，且由于压缩机的效率很高，剩下 2 台机组的出力就能覆盖 100 % 负荷运行。以上论述对案例 A 不适用（基于上面同样的解释），2 台 30 MW 机组都在相当低的部分负荷下运行，且燃机效率不佳。案例 B 操作模式变为 2 + 2 带来的另一个好处也值得一提。由于 2 台机组处于备用模式，这就有机会在同一年对所有机组进行维修工作，这意味着系统的可用率远远高于案例 A，特别是在考虑夏季工况的情况下。

4 Maintenance and Overhauls 维护与大修

Another advantage of operating only 2 out of 4 units for a significant part of the year(i. e. 9 out of 12 months) is the extended time between overhauls. Based on the calculations below, the total number of hours for each turbocompressor unit per year was reduced from 6 570 to 4 928 and, therefore, the time between overhauls could be extended. Based on 3 + 1 units operate during 3 summer months and 2 + 2 units operating during the rest of the year(9 months), if the units were used so that they all ran exactly the same number of hours each year, each unit would run for 4 928 hours every year. Whereas if we account for 3 working units with one standby throughout the year the number of working hours will be as follows: 8 760 × 3 units running = 26 280 /4 units available = 6 570 total hours per unit/year.

配置 4 台机组而大部分时间（如 1 年中 9 个月的时间）只运行其中 2 台机组的另一个优势是可以延长大修的间隔时间（日历时间间隔而不是燃机运行时间间隔）。基于以下计算，每台燃压机组每年的运行时间由 6 570 h 减少到 4 928 h，因此，大修间隔将扩大。基于夏天 3 个月 3 + 1 运行，其余 9 个月 2 + 2 运行，如果机组每年运行的时间相同，每台机组将运行 4 928 h。然而如果我们整年 3 + 1 运行，运行时间如下：8 760 × 3 = 26 280，每台机组平均运行时间 26 280 / 4 = 6 570。

Note that all units run for an equal number of hours to make the calculation simple. However, the customer could push lead machines to reach the agreed time between major inspections(TBI) first, so that all engines do not come up for overhaul at the same time, this would help with the overhaul cost, helping to distribute the overhaul cost over the 30 year cycle. We can even make step further and will see additional benefits of this approach. Accounting for the normal year around operation with 3 units on-line, each turbocompressor will get 6 570 × 30 year = 197 100 required hours of operations. Where as considering 2 + 2 setup for 9 months the total number of the required hours of operations reduced down to 147 840 hours. With modern turbines technology it is not uncommon to see that lifetime operation reaches 150 000 hours. It means that for the lifetime of this project(30 years) there will be no need to buy new set of equipment. This alone makes huge favorable impact on projects economics.

注意，我们假设每台机组运行的时间都相同会使计算更简便。然而，用户需使第 1 台机组在重要检测前到达规定运行时间（TBI），因此所有燃气轮机就不会同时到达大修，这有益于节约大修费用以及分配 30 年的大修费用。我们甚至可以进一步分析，将会发现这种方式带来的额外好处。3 台机组运行，每台透平压缩机机组将运行 6 570 × 30 a = 197 100 h，我们假定 9 个月 2 + 2，总的运行时间降至 147 840 h。对于现代透平技术，工作寿命到达 150 000 h 并不是不常见。这意味着对于这个项目的全寿命运行期间（30 年）不需要再购买新的设备，仅这一点就对项目的经济性产生了巨大影响。

5 Station versus System Availability 站与系统可用率

It is important to recognize the difference between station and pipeline availability. For economic assessments, misunderstanding this issue can lead to the wrong conclusion. Station availability calculations are easy, straight forward and based on simple statistical equations. It is easy to see that fewer units on a compressor station will yield higher availability, assuming the threshold for availability is 100 % of the flow. But is this true for the entire pipeline system? The answer is not easy and requires additional investigation including extensive hydrodynamic analysis using of the statistical methodology. The Monte Carlo method (Santos, 2009) has proved to be the good methodology to determine the pipeline system availability. The statistical portion consists of generating multiple random cases of equipment failure on single or two consecutive compressor stations. The hydrodynamic portion will calculate the maximum throughput that pipeline is available to carry when these failures occur. Based on this extensive and in-depth analysis it can be shown that availability of a pipeline, configured with smaller multiple units, delivers better overall results. The main reason for that outcome is the fact that shutdown of the smaller unit makes lesser impact on the behavior of the entire pipeline. Of course, to have fair results, the availability of the single turbocompressor unit, either smaller 22 MW or larger size 30 MW was identical. It is easy to understand that in our particular case the availability of the station setup with smaller units (case B) was greatly enhanced because of the presence of extra standby unit during winter and fall/spring months when stations setup has 2 +2 configuration.

认识到站场可用率与管线可用率之间的不同是十分重要的。对于经济评估而言,若错误理解这个问题将得出错误的结论。站场可用率计算基于简单的计算公式,简单直接。显而易见,压气站机组较少则可用率将更高。但对于整个管线系统是这样吗?答案没有这么简单,还需要更多的调查,包括通过使用统计学的方法对管道进行大量的水力分析。Monte Carlo 法[3]已被证实是一种较好的用来确定管线系统可用率的数学方法,统计部分包括先假设多种随机的在单个或两个连续的压气站发生设备故障的状况;水力计算部分则会计算出管线在这些机组失效情况下的最大输气能力。基于这个扩展与深入分析可知,管线配置多台小机组时整体可用率会更好。得出这个结论的主要原因是小机组停机对整个系统产生的影响较小。当然,为了有公正的结果,我们必须假设单个透平压缩机组的可用率,不论是 22 MW 或 30 MW 机组,是相同的。这样就很容易理解使用案例 B 的配置站场的可用率更高,因为在其余 9 个月 2 +2 运行时,压气站有额外的配用机组。

6 Effect of Large Unit Shutdown 大机组停机的影响

Examples of the vulnerability are demonstrated based on a typical pipeline scenario with 4 stations. Each station has 2 compressor trains without spares. If one unit in station 2 is lost, the pipeline flow is reduced by 12 %. However, the same 12 % flow reduction can be maintained by also shutting down the surviving unit in station 2. This is due to the necessarily inefficient operation of the surviving unit in station 2, which is forced to operate in choke. If both units are shutdown, stations 3 and 4 will be able to recover the flow, but at a much higher overall efficiency. Thus, shutting both units down reduces the pipeline fuel consumption compared to the scenario with only one unit shut down in station 2. The point of this example is, the failure of one of two large units in a compressor station has more significant consequences than the failure of a smaller unit in a station with three or more operating units. Or, in other words, scenarios with 3 ore more units per station without spare units tend to have a higher flow if one of the units fails, or has to be shut down for maintenance, than scenarios with 2 units per station without spare units.

以 1 条设有 4 座压气站场的典型管线为例,每个站场有 2 台压缩机组且都不安装备用机组。如果第二个站场的 1 台机组停机,整条管线的输送能力将降低 12 %;然而,关闭第二个站场剩下的 1 台机组,整条管线的输送能力也降低 12 %。这是因为第二个站场剩下机组的低效率运行,这种低效率运行将使机组运行至阻塞工况。如果 2 台机组都停机,第三个站场与第四个站场将能够恢复流量,这样整个管道就会运行在更高的效率从而降低总体燃料消耗量。因此,同时关闭 2 台机组会比只关掉第二站的 1 台机组在总体上节约燃料气消耗。这个案例也说明,一个压气站 2 台大机组中 1 台机组失效比一个带多台小机组的站场中 1 台机组失效的影响更大。或者换句话说,每个站场有 3 台或更多机组,在 1 台机组失效或停机维修时,不配置备用机组,可以保持更多流量。

7 Conclusion 结论

The paper has illustrated the different influence factors for the economic success of a gas compression operation. Important criteria include first cost, operating cost (especially fuel cost), capacity, availability, life cycle cost, and emissions. Decisions about the layout of compressorstations such as the number of units, standby requirements, type of driver, and type of compressors have an impact on cost, fuel consumption, operational flexibility, emissions, as well as availability of the station.

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