# 液化天然气(LNG)槽车自增压空温式汽化器的设计计算

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**摘　要**　由于地理、用户使用条件和峰段要求的限制,LNG槽车在输送天然气方面有着巨大的市场需求,是管道输配的重要补充手段。LNG槽车往往需要在没有外加机械动力的情况下,依靠配套的增压汽化器提供压力源,采用顶部气相空间加压方式卸载液体。槽车常配用的汽化器有空温式汽化器和水浴式汽化器两种形式,空温式汽化器使用空气作为热源,节约能源,操作费用低廉。对于长江三角洲地区,常年气候温和湿润,最低气温在零度以下的天数屈指可数,使用空温式气化器完全满足生产要求。文章介绍LNG槽车自增压空温式汽化器的设计计算,其中包括天然气气相和液相物性的计算方法,以及空温式汽化器的热力计算。然后给出空温式汽化器的换热面积和结构尺寸等设计参数。

**主题词**　液化天然气　槽车　自增压空温式汽化器　设计计算

## 天然气物性计算方法

下面主要介绍气体密度、液体密度、比热、粘度、导热系数的确定方法。

1. 气体密度

以真实气体的 SHBWR 方程确定密度,具体形

防汛,施工费用较大,后期维护量大等。本工程采用的是国内目前最为先进的水平定向钻工艺穿越河流技术,所用的穿越设备都是目前国内最为先进的,从而成功地穿越了黄河,其穿越长度、深度都是目前国内同类工程之最,同时,也打破了黄河中上游水平定向穿越禁区的说法。工程总投资为 350 万元,比采用其他施工方法节约投资近 200 万元,且管道在穿越段的安全有可靠保障。

2. 认识和经验教训

1) 实践证明采用水平定向穿越大型河流—黄河中上游在技术上是可行的,同时也是十分经济的。

2) 通过前三次的穿越失败可以看到,黄河中上游的穿越施工区域地质情况较为复杂,在掌握一手地质资料的前提下,应及时根据现场实际施工情况及时与甲方和设计方联系协商,认真总结失败原因,制定相应的措施:①发现地质情况与原地质资料不符,及时补打地质勘查井获取准确资料;②针对特殊硬地层和实际的地质情况,在符合设计的基础上改变穿越曲线,入土角由原来的 11°改为 10°,同时为回避距入土点 800 m 处的两透镜体,决定在 710 m 处抬高 5 m,然后水平钻进与原曲线重合;③及时改进泥浆配置技术,添加 3 %的改型淀粉,提高泥浆粘度;添加 3 %的磺化沥青、3 %的石棉灰等添加剂以增强泥浆携砂、防塌能力,提高孔内泥浆压力;④改进预扩孔回拖技术,由过去的一次扩孔第二次回拖改变为采用多级预扩孔后回拖;⑤对预扩孔工艺进行改进,预扩孔每 330 m 加一个松土器,松土器上有两个 2 mm 的孔,可以喷泥浆减少冲洗管的阻力。

3) 在建设方、监理方的指导下,成功解决砂质地层施工技术问题,突破穿越铁板砂这一施工禁区,为以后的穿越提供技术参考和经验。

4) 水平定向穿越虽然在投资上优于其它中施工办法,但其风险性较大,应在今后的施工中准确掌握穿越段的地质情况,确保穿越成功。

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式为：

$$p = \rho RT + \left(B_0RT - A_0 - \frac{C_0}{T^2} + \frac{D_0}{T^3} - \frac{E_0}{T^4}\right)\rho^2 + \left(bRT - a - \frac{d}{T}\right)\rho^3 + \alpha\left(a + \frac{d}{T}\right)\rho^6 + \frac{c\rho^3}{T^2}(1+\gamma\rho^2)\exp(-\gamma\rho^2) \quad (1)$$

纯组分上式各个系数可以参见文献〔1〕,表1给出了混合工质参数的混合法则。

由SHBWR方程计算密度需要进行迭代计算,因为天然气中$CH_4$占80%以上,迭代初值可以取状态理想气体$CH_4$的密度。

2. 液体密度

由于液体的可压缩性很小,所以过冷液体的密度与饱和状态的密度可以认为相等。纯净液体的密度采用由PRSK方程推导校正出的公式计算：

$$\frac{\rho_s}{\rho_c} = \beta[1 + \delta\sqrt[3]{f(T_r - 1)}] \quad (2)$$

上式中,$\rho_s$、$\rho_c$分别是液体饱和密度和临界密度,$\delta$是单组分工质的特征量,$T_r$是对比温度,$\beta$、$f(T_r)$确定可以参考文献〔2〕。

液体LNG密度的混合法则如表2给出。

3. 比热

表1　混合工质SHBWR方程参数确定的混合法则

| | | | |
|---|---|---|---|
| $B_0 = \sum_i x_iB_{0i}$ | $A_0 = \sum_i\sum_j y_iy_j\sqrt{A_{0i}A_{0j}}(1-k_{ij})$ | $C_0 = \sum_i\sum_j y_iy_j\sqrt{C_{0i}C_{0j}}(1-k_{ij})$ | $\gamma_i = \left(\sum_i y_i\sqrt{\gamma_i}\right)^2$ |
| $a_i = \left(\sum_i y_i\sqrt[3]{a_i}\right)^3$ | $b_i = \left(\sum_i y_i\sqrt[3]{b_i}\right)^3$ | $c_i = \left(\sum_i y_i\sqrt[3]{c_i}\right)^3$ | $d_i = \left(\sum_i y_i\sqrt[3]{d_i}\right)^3$ |
| $\alpha_i = \left(\sum_i y_i\sqrt[3]{\alpha_i}\right)^3$ | $D_0 = \sum_i\sum_j y_iy_j\sqrt{C_{0i}C_{0j}}(1-k_{ij})^4$ | $E_0 = \sum_i\sum_j y_iy_j\sqrt{C_{0i}C_{0j}}(1-k_{ij})^5$ | 说明：$y$表示摩尔成分 |

表2　液体LNG密度的混合法则

| | | | |
|---|---|---|---|
| $T_{cm} = \sum_i x_iT_{ci}$ | $\delta_m = \sum_i x_i\delta_i$ | $f_m(T_r) = \sum_i\sum_j x_ix_j\sqrt{f(T_r)_i f_j(T_r)}$ | $\rho_{cm}^{-3/4} = \sum_i x_i\rho_{ci}^{-3/4}$ |

对于液体温度变化范围不大,可以当作定比热处理。纯组分的理想气体与实际气体的比热分别为

$$c_p = a + bT + cT^2 + dT^3 \quad (3)$$

$$c_p = c_p^{(0)} + \Delta c_p \quad (4)$$

系数$a$、$b$、$c$、$d$可以参阅文献〔1〕,$\Delta c_p$可以通过L-K方程确定。

4. 粘度

液体LNG粘度采用文献〔2〕的关系式：

$$\lg(\mu + 0.8) = 100(T/100)^b \quad (5)$$

其中,$b = \sum_i \frac{x_i}{b_i}$,$b_i$可以参阅文献〔2〕。

纯组分气体的粘度及混合气体粘度混合法则可以参考文献〔1〕。

5. 导热系数

液体LNG的导热系数可以作为常数处理,气体导热系数由表3给出。

## 空温式汽化器设计计算

空温式汽化器根据用途分为增压式和供气式两类。供气式空温式汽化器给出具有一定过热度的带压气体满足用户的需要,所以其包含蒸发部与加热部两段,如图1所示;增压式空温式汽化器只是为了

表3　气体导热系数计算参照表

| | | |
|---|---|---|
| 烃类低压气体 | $\lambda = (14.52T_r - 5.14)^{2/3}c_p/(10^6\Gamma)$ | $\Gamma = T_c^{1/6}M^{1/2}p_c^{-2/3}$ |
| 烃类高压气体 | $(\lambda - \lambda^{(0)})\Gamma z_c^5 = 14.1\times10^{-8}[\exp(0.535\rho_r) - 1]$　$(\rho_r \le 0.5)$<br>$(\lambda - \lambda^{(0)})\Gamma z_c^5 = 13.1\times10^{-8}[\exp(0.67\rho_r) - 1.069]$　$(0.5 < \rho_r \le 2.0)$<br>$(\lambda - \lambda^{(0)})\Gamma z_c^5 = 2.976\times10^{-6}[\exp(1.155\rho_r) + 2.016]$　$(2.0 < \rho_r \le 2.8)$ | |
| 混合气体 | $\lambda_m = \sum_i \frac{y_i\lambda_i}{\sum_j y_jA_{ij}}$<br>$A_{ij} = \frac{1}{4}\left[1 + \left(\frac{\mu_i}{\mu_j}\right)\left(\frac{M_i}{M_j}\right)^{3/4}\sqrt{\frac{1+S_i/T}{1+S_j/T}}\right]^2\frac{1+S_{ij}/T}{1+S_i/T}$ | |

提供输液的压力,并且不能给槽车储罐带来额外冷损,所以其只具有蒸发部,以饱和温度气体进入槽车储罐。空温式汽化器导热管是将散热片和管材挤压成型的,导热管的横截面为星形翅片(见图1)。

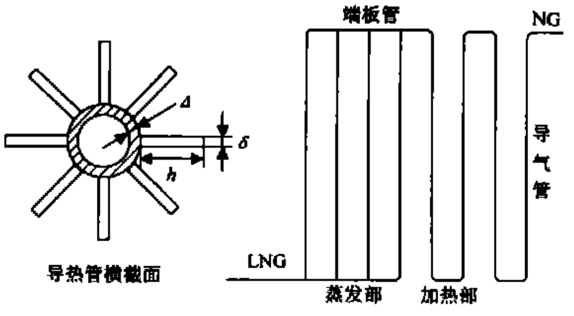


图1　星形翅片空温式汽化器示意图

1. LNG槽车对增压气体的要求

为了维持LNG槽车输送液体过程稳定,增压气体必须满足:①槽车容器顶部气相空间必须达到工作压力,并且在槽车额定压力下输送液体可以达到安全而快速;②设计中空温式汽化器给槽车提供的气体具备推动液面做功的能力,又不必造成额外的液体蒸发,供气温度维持饱和温度;③槽车的补气体积等于槽车的输液体积。为了分析方便,忽略导气管的热交换,对槽车液体和汽化器内气体组成的热力系统,运用能量平衡方程可有

$$Q = \rho u(i_2 - i_1) + pu \tag{6}$$

式中:$\rho$为液体密度;$u$为液面下降速度;$i_1$为进入汽化器的过冷液体焓值;$i_2$为汽化器提供饱和气体焓值。我们根据上式计算出对汽化器热交换量的要求。

2. 汽化器的热力计算

通常星形翅片空温式汽化器采用直肋片管,具体单个肋片尺寸参见图1示意。

直肋片管基管壁厚按照GB-150要求和方法确定,其计算公式为

$$\Delta(\mathrm{mm}) = \frac{pD}{2[\sigma]^t + p} + \Psi \tag{7}$$

式中:$D$为基管外径;$[\sigma]^t$为设计温度下管子的许用应力(单位为MPa);$\Psi$是考虑壁厚负偏差、裕量在内的管壁附加量(单位为mm)。

从传热学角度,肋片起换热作用的条件为$\frac{2\lambda}{\alpha\delta} > 1$($\lambda$为肋片材料的导热系数、$\alpha$为对流换热系数);同时从优化换热的经验,肋片间距$b$与高度$h$必须满足约束方程$(Gr \cdot pr)\frac{b}{h} \approx 50$,这就是肋片尺寸的一个约束条件。从而得到肋片间距为$b = \frac{50h\upsilon^2}{g\beta(T_{sur} - T_f)\cdot pr}$($g$为重力加速度、$\beta$为空气热膨胀率、$\upsilon$为空气运动粘度)。

一般情况下,肋片高度远远大于其厚度,肋端可以视为绝热处理,单个肋片的换热量为

$$q = \lambda m(\delta L)(T_{sur} - T_f)\, th(mh) \tag{8}$$

上式中$L$为肋片长度,$m = \sqrt{\frac{2\alpha(L+\delta)}{\lambda L\delta}}$、$th(mh) = \frac{e^{2mh} - 1}{e^{2mh} + 1}$。

肋片数为

$$N = \frac{\pi D}{\delta + b} \tag{9}$$

单根肋片管的总换热量为:

$$Q_1 = Nq + \alpha(T_{sur} - T_f)(\pi D - N\delta) \tag{10}$$

考虑到肋基温度沿长度方向的变化,运用对数温差求取$(T_{sur} - T_f)$

$$(T_{sur} - T_f) = \frac{\Delta T_{max} - \Delta T_{min}}{\ln(\Delta T_{max}/\Delta T_{min})} = \frac{(T_{sur} - T_L) - (T_{sur} - T_G)}{\ln[(T_{sur} - T_L)/(T_{sur} - T_G)]} \tag{11}$$

需要的肋片管总根数为

$$N' = Q/Q_1 \tag{12}$$

通常导气管长度的选取根据汽化器对换热面积裕量的要求而定。

## 结　论

LNG槽车自增压空温式汽化器的设计计算对稳定LNG输送、保证供应气体状态参数、节约材料消耗等有重要意义。长江三角洲地区是西气东输工程重点用户地区,空温式汽化器有着广阔的市场需求。本文首先给出天然气物性计算方法,然后给出空温式汽化器的换热面积和结构尺寸等的计算方法。这为工程设计提供物性计算参照与指导,对优化、缩短LNG相关设计有着重要作用。

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## APPLICATION OF WET PROCESS DESULPHURIZING TECHNOLOGY IN SINGLE WELL NATURAL GAS EXPLOITATION

Zheng Guoshu and Chen Rui (Yu-Da Natural Gas Multipurpose Utilization Company of East Sichuan Drilling Company of SPA). *NATUR. GAS IND.* v. 22, no. 3, pp. 81～83, 5/25/2002. (ISSN1000 - 0976; **In Chinese)**

**ABSTRACT:** At present, the wet process desulphurizing technology is widely utilized in large-scale desulphurizing plants and not applied in single wells. Many high sulfurous gas wells, however, are far from the desulphurizing plants. In order to make the natural gas resources exploited from these wells be turned into the commercial gas utilized, a great sum of funds are needful for building up gas pipeline for desulphurization to transport the high sulfurous gas to the desulphurizing plants, which limits the exploitation of the high sulfurous natural gas in middle-low production wells. Therefore it is necessary to study the application of the wet process desulphurizing technology to single wells. In the paper, the basic principle and technological processing of single-well wet process desulphurization are expounded and determined; and several key techniques which need to be solved for applying the wet process desulphurizing technology to single wells are pointed out. Through utilizing such a technology in the exploitation of shallow well Tei - 1 —a high sulfurous gas well, it is proved that such a gas desulphurizing technology is economic and reasonable with an obvious effect —being able to get qualified natural gas by purifying, thus opening up a vast range of prospects for utilizing the high sulfurous natural gas resources in the remote gas wells with middle-low production rates.

**SUBJECT HEADINGS:** Gas well, Single well, Gas desulfurization, Application

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## HORIZONTALLY ORIENTING CROSSING HUANGHE RIVER ENGINEERING OF CHANGNING GAS PIPELINE

Zhang Xingsheng (Changning Natural Gas Ltd. of Ningxia). *NATUR. GAS IND.* v. 22, no. 3, pp. 84～86, 5/25/2002. (ISSN 1000 - 0976; **In Chinese)**

**ABSTRACT:** Changning gas pipeline is the first long-distance one in Ningxia. It starts from Shaan-Gan-Ning gas field in the east to Yinchuan of Ningxia in the west and has an overall length of 294 km, pipe diameters of Ø426 mm ×6, 7, 7 mm and designed annual throughput rates of 400 $\times 10^6$～600 $\times 10^6 m^3$ at transfer pressure of 4.5 MPa. Crossing Huanghe River engineering is located at the vicinity of Ren Village, Leitai - 2 Team, Yongning County, the Ningxia Hui Autonomous Region in the middle-upper reaches of the Huanghe River. The formation at the cross section is composed of channel deposits with unconsolidated sands. When water content is large, it is of the property of drift sands. Such engineering is the controlling one of Changning gas pipeline project. It is designed by the Langfang Pipeline Design Institute of PCL, surveyed by the Yisilan Geological Survey Team of Ningxia and constructed by the No. 2 Pipeline Company and the No. 3 Pipeline Company, PCL. The first corossing in the middle-upper reaches of the Huanghe River has been finished in China by use of horizonally orienting crossing technology and it is the longest and deepest crossing engineering in all of the same ones in China, thus providing valuable and successful experience for pipeline's horizontally orienting crossing large-sized rivers.

**SUBJECT HEADINGS:** Shaan-Gan-Ning, Ningxia, Natural gas pipeline, Horizontal orientation, Crossing, Engineering

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## DESIGN CALCULATION OF SELF-PRESSURIZED AIR-HEATED EVAPORATOR FOR LNG TRANSPORTATION TANK

Zhang Cunquan and Xu Lie (Shanghai Jiaotong University). *NATUR. GAS IND.* v. 22, no. 3, pp. 86～88, 5/25/2002. (ISSN 1000 - 0976; **In Chinese)**

**ABSTRACT:** Because of the limitation of the geographical and customer-used conditions and peak-zone demand, the liquefied natural gas (LNG) transportation tank is of great market potentialities in transporting natural gas, being an important supplementary means for pipeline transmission and distribution. The pressure source is always needed to be provided by a matched pressurized evaporator for the LNG transportation tank under the condition of having no external mechanical power, i. e. to apply self-pressurized mode in the top gaseous space to offloading liquid. There are two kinds of evaporator matched for the LNG transportation tank, i. e. air-heated evaporator and aquathermal evaporator, the former may economize on both energy source and investment, taking air as its heat source. The air-heated evaporator can fully meet the demand for offloading liquid at the Yangtze River delta region where the climate throughout the year is gentle and humid and only very few days' lowest atmospheric temperature was below zero centigrade. The design calculation of the self-pressurized air-heated evaporator for LNG transportation tank, including the gas phase and liquid phase physical property calculation of natural gas and the thermal calculation of the air-heated evaporator, are introduced, then the design parameters, as the heat exchange area and physical dimensions, etc., of the air-heated evaporator are given out in the paper.

**SUBJECT HEADINGS:** Liquefied natural gas, Transportation tank, Self-pressurized air-heated evaporator, Design, Calculation

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## LNG LAND STORAGE AND TRANSMISSION IN CHINA

Xu Lie, Li Zhaoci and Zhang Jie (Shanghai Jiaotong University), Xu Yongsheng (Zhangjiagang Sanctum Chemical Machinery Co. Ltd.). *NATUR. GAS IND.* v. 22, no. 3, pp. 89～91, 5/25/2002. (ISSN 1000 - 0976; **In Chinese)**

**ABSTRACT:** Liquefied natural gas (LNG) land storage and transmission is an absolutely necessary part in natural gas industry, which is of great significance in promoting the development of natural gas industry. The status of the natural gas liquefying, LNG storage and transmission and LNG acception station, etc., in existing LNG storage and transmission market as well as the technical level of key techniques such as supporting, insulation, safety and flowing path design, etc., in the LNG storage and transmission equipment in China are introduced in the paper. And some suggestions on developing the LNG storage and transmission equipment industry are proposed finally.

**SUBJECT HEADINGS:** Land, Liquefied natural gas, Storage, Transportation

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## DESIGN AND ANALYSIS OF NATURAL GAS LIQUEFYING DEVICE WITH A DELIVERABILITY OF TWENTY THOUSAND CUBIC METERS PER DAY

Niu Gang, Wang Jing (Shanghai Jiaotong University) and Huang Yuhua (Dalian University of Technology). *NATUR. GAS IND.* v. 22, no. 3, pp. 92～95, 5/25/2002. (ISSN 1000 - 0976; **In Chinese)**

**ABSTRACT:** As the "LNG demonstrating project in North Shannxi gas field", the natural gas liquefying device with a deliverability of 20 $\times 10^3 m^3/d$, which was built up and went into operation in January 1999, is the guiding project of developing LNG industry in China and is the first small LNG industrialized device in China. The major characteristics of the device are: ①to make use of natural gas expanding refrigeration recycle; ②to purify material gas by both low temperature methanol washing and molecular sieve drying; ③to get cryogenic refrigeration by gas wave machine and turbin expanding motor; ④to take advantage of gas engine as the power of recycle gas compressor; and ⑤to make use of the exhaust gas of gas engine as the thermal source of heating molecular sieve regeneration gas. All the units of the device are made in China and this device's being successfully put into operation has provided experience for producing LNG by use of the natural gas exploited from the remote oil and gas fields in China.

**SUBJECT HEADINGS:** Natural gas, Liquefaction device, Design, Technological process, Simulation, Calculation

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## MATHEMATICAL MODEL AND ALGORITHMS OF HYDRAULIC ANALYSIS OF CITY NATURAL GAS PIPELINE NETWORK

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