# 高炉煤气集输系统计算机仿真

林　枫　韩洪佳　罗建忠　闫锦生
(哈尔滨七〇三研究所 )

[摘要 ] 针对某钢铁厂高炉煤气集输工程,在方案选择的基础上,运用计算机数字仿真这一技术,对系统投运后的工作状况及各用户的压力、流量特性进行了预测。从理论上论证了方案的可行性与可靠性,得出了一些有意义的结论,并为下一步设计中的参数优化与选择打下了基础。

关键词　数字仿真　燃气输配
分类号　TQ547° 8

## 0　前言

某钢铁厂现有 75 $m^3$ 高炉两座,并配有一套煤气系统。在实际运行中这套煤气系统存在许多问题,主要是: 第一,加压站不能正常工作。主要原因是煤气中的大量油性灰尘粘在压缩机叶轮上,导致动平衡破坏引起剧烈振动。第二,用户的煤气压力波动大,波动幅度高达 1. 96 kPa

目前工厂为了适应钢铁生产要求,决定再建一座新高炉。建成后煤气产量将大幅度增加,为了充分利用能源,并为用户提供压力稳定的煤气,工厂计划改造原煤气系统,实施一项煤气集输工程,并曾委托某设计单位作过方案设计,该方案将新高炉所产煤气首先进入湿式煤气柜 (气柜压力为 $P_N$= 1. 47 /1. 96 /2. 45 kPa),然后再与原有 75 $m^3$ 高炉煤气会合进入加压站,经新装备的大流量压缩机加压后送至各用户,见图 1。厂方仔细研究后认为方案并没有解决旧系统中所存在的问题,而且在压气机入口会合处由于新旧高炉煤气压力不同可能会出现相互干扰问题,为了做到对工程更有把握,又委托我单位另做方案设计。

我们经过仔细研究与现场调查,推出了图 2所示的方案。该方案将低、中压煤气分开、分别供不同的压力要求的用户使用,充分利用了新高炉的压力,并且在中压系统中采用干式煤气柜来进行稳压,取消了压缩机。可以看出这个方案充分利用了压力能,因取消了压缩机可节省大量的运行维护费用。但是这个系统能否稳定工作以及投入运行后用户能否得到压力稳定的煤气却是这个方案成立的关键所在。为了解决这个问题,我们采用了计算机仿真这一技术。

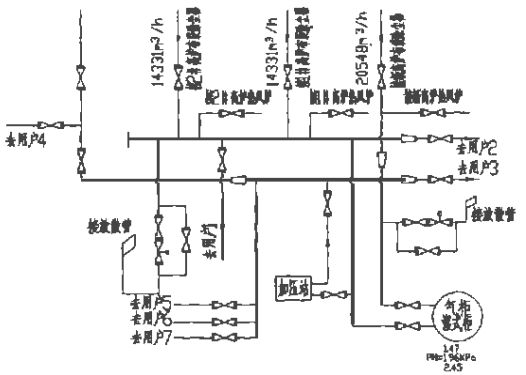


图 1　原煤气系统

## 1　计算机仿真

1. 1　仿真就其模型而言可分为物理模型和数学型。近年来随着计算机技术的飞速发展,通过建立数字模型,运用计算机进行数字仿真作为手段来获得系

收稿日期　1997- 05- 29

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved.　http://www

统实际工作状况的设计概念以其有效性高而耗资低的特点得到广泛应用。仿真技术目前在航空、航天、造船以及其它高科技工业领域已被作为一项成熟技术运用于设计、运行之中。

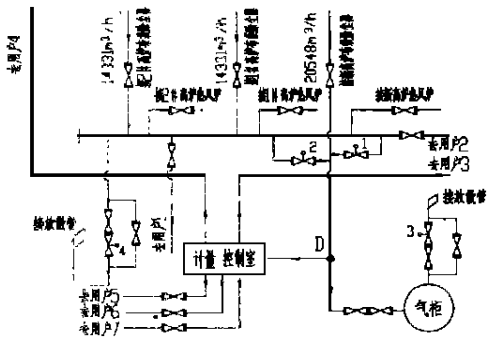


图 2 新煤气系统

1.2 问题的提出

根据前面我们推出的方案,首先要考虑以下几方面的问题:

1.2.1. 系统能否稳定工作;

1.2.2. 当高炉煤气压力变化时,各用户的压力变化;

1.2.3. 用户的用气量变化对整个煤气系统的影响;

1.2.4. 气柜的设计压力变化,会对系统有什么样的影响;

1.2.5. 各段管路管径变化会对系统有何影响。

对这些问题的解答,我们采用了仿真技术。

1.3 稳态数学模型的建立

考虑了本系统的特点、工程工艺及精度要求,本文采用了稳态数学模型。

在管道流动中,燃气微小质量 $F\mathrm{d}x$ 的运动方程为:

$$\frac{\partial(\mathrm{d}k)}{\partial f}+\frac{\partial(\mathrm{d}k^2)}{\partial X}=-\frac{\partial P}{\partial X}-g\mathrm{d}\sin\alpha-\frac{\lambda}{d}\cdot\frac{k^2}{2}\cdot\mathrm{d} \tag{1}$$

其中: d 燃气密度 k 燃气流速 f 时间

D 燃气压力 λ 摩擦阻力系数 d 管径

上述方程中,经分析表明[5]对流项只在燃气流速接近声速时才有意义,而惯性项只在管道中燃气流量随时间变化极大时才有意义。我们考虑稳态流动,因此可略去惯性项 $\frac{\partial(\rho\omega)}{\partial\tau}$、对流项 $\frac{\partial(\rho k^2)}{\partial l}$ 及重力项 $g\rho\sin\Gamma$,得到简化运动方程:

$$-\frac{\partial P}{\partial X}=\frac{\lambda}{d}\cdot\frac{k^2}{2}\cdot\mathrm{d} \tag{2}$$

对于稳定流动的燃气管道,有如下连续方程和气体状态方程

$$\mathrm{d}k=C(\mathrm{Const}) \tag{3}$$

$$P=Z\cdot\mathrm{d}\cdot R\cdot T \tag{4}$$

厂区煤气管网加外保温层,因此近似考虑煤气温度为定值。

对于管道节点,如图 3,根据质量守恒有:

$$m_1+m_2=m_3 \tag{5}$$

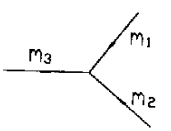


图 3

对于煤气柜有: $\int_0^t m_D\cdot\mathrm{d}t=Q\cdot\mathrm{d}$ (6)

其中: $m_D$ 进出气柜的煤气质量流量

$t$ 气柜有效工作时间 $Q$ 气柜容积

对于系统中各段管路和节点,都能得到以上类似一组方程,这样我们得到若干方程组成的方程组(略)

1.4 数学模型的求解

可以看到上面得到的系统的数学模型为一组非线性方程组。目前对于非线性数学模型的求解,如燃气轮机数学模型的求解,广泛采用的是 Newton-Raphson算法。这种算法精度高,收敛速度也较快。

煤气系统是由多个管道及附件组成的整体,在稳定工况下工作时,要受到能量、流量及压力等平衡条件的限制,如果一旦平衡条件破坏,则能量、压力、流量等参数就会产生不平衡量,也被称为残量。由反应不平衡量的方程构成的方程组称为残量方程组,用矢量的形式可表示成:

$$\vec{E}=f(\vec{X})\qquad \vec{X}\in R^n \tag{7}$$

求解模型(稳态)就是要在 $\vec{E}=0$ 的条件下解出变量 $\vec{X}$,变量 $\vec{X}$ 的所有元素必须保证 $\vec{E}$ 是零向量。实际上残量 $\vec{E}$ 一般不能用 $\vec{X}$ 解析式来表达。当自变量 $\vec{X}$ 有微小变量 $\Delta\vec{X}$ 时,残量的相应变化 $\Delta\vec{E}$,根据 Taylor公式,两者之间的关系可以表示为

$$\Delta\vec{E}=J(\vec{E},\vec{X})\cdot\Delta\vec{X} \tag{8}$$

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www

式中 $J(\vec{E},\vec{X})$为 $n\times n$雅可比矩阵

$$J(\vec{E},\vec{X})=\begin{bmatrix}\frac{\partial E_1}{\partial X_1} & \frac{\partial E_1}{\partial X_2} & \cdots & \frac{\partial E_1}{\partial X_n}\\ \frac{\partial E_2}{\partial X_1} & \frac{\partial E_2}{\partial X_2} & \cdots & \frac{\partial E_2}{\partial X_n}\\ \cdots & \cdots & \cdots & \cdots\\ \frac{\partial E_n}{\partial X_1} & \frac{\partial E_n}{\partial X_2} & \cdots & \frac{\partial E_n}{\partial X_n}\end{bmatrix} \qquad (9)$$

方程组 (8)也可以表示为

$$\vec{E}_2-\vec{E}_1=J(\vec{E}_1,\vec{X})(\vec{X}_2-\vec{X}_1) \qquad (10)$$

在仿真模型中初猜 $\vec{X}$值之后,根据模型方程可求得残量 $\vec{E}$,采用差商的方法求出残量 $\vec{E}$关于 $\vec{X}$在 $\vec{X}_1$点的 $J$矩阵。为使下一点残量 $\vec{E}_2=0$(实际上要经过多次迭代才能达到)则下一点应为:

$$\vec{X}_2=\vec{X}_1-J^{-1}(\vec{E},\vec{X})_{\vec{x}=\vec{x}_1}\vec{E}_1 \qquad (11)$$

将上式一般化得到 Newton- Raphson迭代式

$$\vec{X}_{k+1}=\vec{X}_k-J^{-1}(\vec{E},\vec{X})_{\vec{x}=\vec{x}_k}\vec{E}_k$$

本模型中选取关键节点的流量构成残量 $\vec{E}$,压力构成变量 $\vec{X}$。

### 1.5 仿真程序编制

在上述模型及算法基础上,采用 FORTRAN语言编制了微机上运行的仿真程序。

程序流程图见图 4

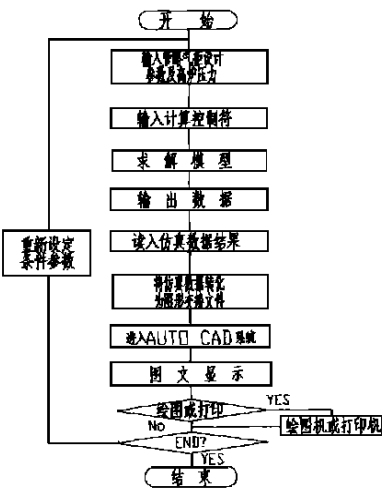


图 4

为了使得仿真结果能精确地转化为图形(曲线状)仿真中增加了后处理程序,将结果数据转化为图形交换文件,借助于 AutoCAD来显示并输出图形结果。

## 2 仿真结果分析

图 5是高炉出口处压力变化,对系统各点煤气压力的影响曲线(以用户 6和节点 D为例)。ab段为高炉压力小于 D点压力的情况下,由于气柜的稳压作用,ab段为一水平直线,此时用户压力和流量由气柜维持。bc段为过渡段,在这一段内气柜和高炉同时向用户供气,随着高炉压力的提高,气柜逐步由放气状态转入充气状态,用户压力也稍有提高。cd段为 D点压力大于气柜压力的情况,此时,高炉供气量大于用户的用气量,气柜处于充气状态。当气柜充满时,多余煤气通过放散口放散掉。由图可见 ab段和 cd段均为水平直线(cd近似于水平直线),说明在这两个区域用户压力为一衡定值,只有 bc段内用户压力稍有变化,说明我们的方案完全能够起到稳压作用,满足了煤气用户的要求。

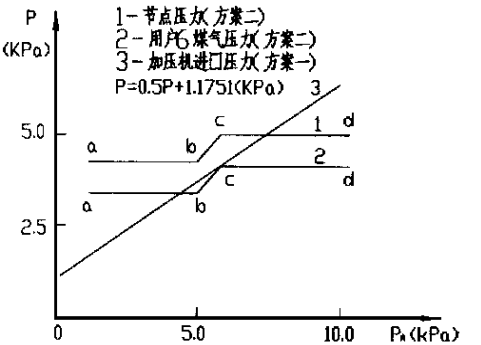


图 5 高炉煤气压力变化对各点煤气压力的影响

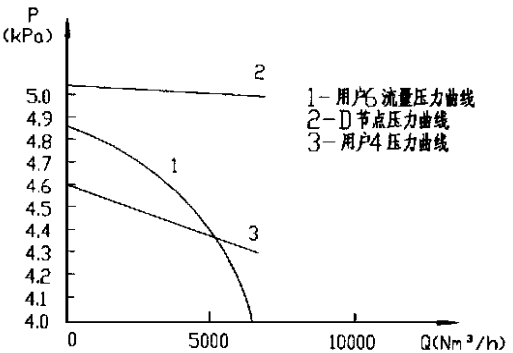


图 6 流量变化与压力的关系曲线

图 6是系统中某个用户煤气流量变化对某个系统的影响。以用户 6为例,当用户 6煤气流量变化

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www

时,用户 6煤气压力也相应变化。流量增加,由于管路阻力增大,所以,煤气压力也相应有所降低。由图可以看出,在设计管径条件下,曲线 2和曲线 3要比曲线 1平坦得多。说明用户 6流量变化,对节点 D压力和用户 4煤气压力的影响较小,在允许范围之内。通过大量仿真计算表明(结果略),系统中任一用户流量在正常范围内变动,不会影响其它用户的煤气正常使用。

图 7是不同的气柜设计压力时对系统各点压力的影响。由图中曲线可知,气柜设计压力提高,系统中各点的压力水平均提高。由于用户所需煤气压力

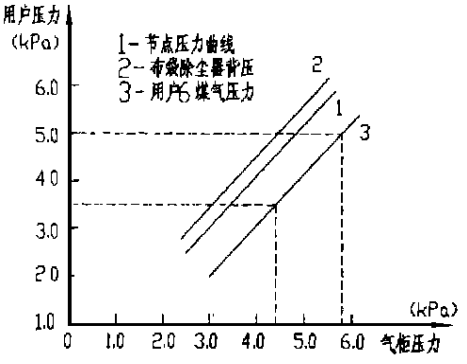


图 7 不同气柜设计压力对系统各点压力影响

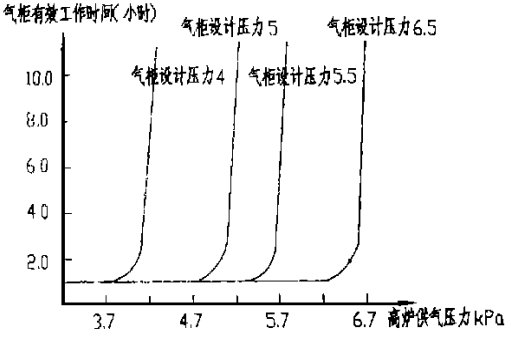


图 8 气柜有效工作时间随高炉供气压力变化曲线

值为 3.5~ 5 kPa,对应气柜设主压力范围为 4.3~ 5.8 kPa。

图 8是针对 2万立方米干式气柜,用户用气量为 18 700标米$^3$/小时,得到气柜在不同的设计压力所对应的有效工作时间。气柜有效工作时间是指高炉产气量小于用户所需的煤气量时,气柜靠内部储气所能维持工作的时间。气柜的有效工作时间与其设计压力、设计容积以及高炉的供气压力有关。以图中气柜设计压力为 5 kPa的曲线为例,当高炉出口压力小于 5.6 kPa时,用户所需煤气由高炉和气柜供给,此时气柜所有气量逐渐减小。高炉出口压力大于 5.6 kPa时,高炉产气量可以满足用户的要求,此时用户的煤气全部由高炉供给,气柜的有效工作时间为无穷大。当高炉出口压力小于一定值时,用户的气量全部由气柜供应,此时 2万立方米气柜的有效工作时间约 1.0小时(如用户需要气柜有效工作时间延长可以增大气柜的容量)。

以上仅为具有代表性的部分仿真结果。其它计算结果略。

## 参 考 文 献

1. 熊光愣主编. 计算机仿真及应用. 电子工业出版社, 1982. 2
2. 李庆扬,王能超,易大义. 数值分析. 华中工学院出版社, 1982
3. 管彦深,王仲生. 燃气轮机的数学模型及数学模拟. 机械工程学报 1985, 21(3)
4. 储钟武,何铁良,崔明根,林江编译. 数值分析. 黑龙江科学技术出版社, 1987
5. 哈尔滨建筑工程学院,北京建筑工程学院,同济大学编. 燃气输配. 中国建筑工业出版社 1986. 7

作者简介: 林枫 男 1966年生 博士研究生。主要从事燃气轮机装置及应用研究。
(通讯处: 150036 哈尔滨市 77信箱 4分箱)

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www

船用大功率自动同步离合器试验= **Experimental Design of High-power Automatic Synchronizing Clutches for Ships** [刊,中]/Wei Junbo(Harbin No. 703 Research Institute)//Journal of Engineering for Thermal Energy & Power.- 1997,12(5).- 351~ 353

On a high-power automatic synchronizing clutch test rig developed by the No. 703 Institute and by the use of a computer-based data acquisition system a series of tests involving the engagement/disengagement of a clutch under no-load conditions were completed, thereby providing test facilities and methods for carrying out an in-depth study of dynamic characteristics of marine high-power automatic synchronizing clutches. **Key words** automatic synchronization, clutch, test rig, test and measurement

焦载热部分气化燃煤联合循环系统性能分析= **Performance Analysis of a Coke Carried Heat Partial Gasification Coal-fired Combined Cycle** [刊,中]/Xu Xiangdong, Zhao Li(Tsinghua University)//Journal of Engineering for Thermal Energy & Power.- 1997,12(5).- 354~ 357

Heat carried partial gasification combined cycle pertains to a novel coal-fired combined cycle-based electrical power generation technology developed by the Thermal Energy Department of Tsinghua University. As a result of continuous study over the years and the operating experience accumulated therein the said technology has seen significant improvement. Recently, as an improved version of the system, coke carried heat partial gasification combined cycle has been proposed and the coke carried heat boiler and gasification boiler have already been built at the Tsinghua Power Station with a cold-state commissioning test performed. On the basis of the heat carried cycle and by changing gas components and other parameters an analysis is conducted of the coke carried heat system, which enables the authors to make the conclusion that the gas quality and flow rate play a key role in ensuring the high performance of the combined cycle system as a whole. **Key words** heat carried gasification, coke carried heat partial gasification, performance calculation

舰船锅炉总体方案的经济性和重量尺寸指标分析= **An Analysis of the Economic Aspect and Weight-dimension Index for a Naval Bolier Comprehensive Scheme** [刊,中]/Chen Qiduo, Liu Changhe, et al (Harbin No. 703 Research Institute)//Journal of Engineering for Thermal Energy & Power.- 1997,12(5).- 358~ 360 **Key words** naval boiler, economic aspect, weight and dimensions

谐振子系统量子卡诺热泵的最佳特性参数= **Optimal Performance Parameters of a Harmonic Oscillation Quantum Carnot Heat Pump** [刊,中]/Wu Feng, Sun Fengrui, Chen Lingen(Naval Engineering Academy)//Journal of Engineering for Thermal Energy & Power.- 1997,12(5).- 361~ 364

The optimum performance of a quantum heat pump is studied. Derived is the relationship between the quantum heat pump optimum pump heat rate $\pi_0$ and pyrogenicity $\psi$. Also obtained are the optimum performance parameters with $\pi_m$ and E serving as objectives. **Key words** harmonic oscillation, quantum heat pump, optimum performance

高炉煤气集输系统计算机仿真= **Computer Simulation of Blast-furnace Gas Gathering and Transportation System** [刊,中]/Lin Feng, Han Hongjia(Harbin No. 703 Research Institute)//Journal of Engineering for Thermal Energy & Power.- 1997,12(5).- 365~ 368

With respect to the blast-furnace gas gathering and transportation system of an iron and steel works a computer-based mathematical simulation technology is used based on the selection of schemes to forecast the system operationg conditions after its commissioning and the specific features of pressure and flow rate employed by various end-users. Through a theoretical justification of the feasibility and reliability of the selected

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www

scheme some meaningful conclusions were obtained, which can serve as a solid basis for parameter optimization and selection in future design work. **Key words**: gas turbine, simulation technology, mathematical model

太阳能集热器系统的四维热网络动态仿真模型= **Dynamic Simulation Model of a Four-dimensional Heat Network for a Solar Energy Collector System**[刊,中]Chou Qiaoli, Ye Hong, et al (China National University of Science & Thechonology) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 388~392

The authors have for the first time come up with the conception of a unit(differential) section separate node point heat resistance and heat capacity four-dimensional heat network for a solar energy collector system and on this basis set up a heat collection process dynamic emulation model for the solar energy collector system with a cavity absorber-trough paraboloidal mirror. Under the conditions of a variation of all outside driving forces this model can be used not only to determine the variation of temperature distribution with time of any section of a component but also obtain the spatial distribution of the temperature of each component at any time along the collector system, thereby realizing for the first time the four-dimensional dynamic emulation of the operating conditions of a large-sized solar energy collector. **Key words**: cavity absorber, solar energy collector, Four-dimensional heat network dynamic emulation

机组旁路系统减温减压装置热力特性的计算机分析= **Computer Aided Analysis of the Thermodynamic Properties of a Pressure and Temperature Reduction Device for a Steam Turbine Bypass System**[刊,中]/Zhang Qi, Wang Shizhong, Wang Huaibin(Harbin Institute of Technology) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 369~373

On the basis of an IFC formula and one-dimensional search method realized are a computer-aided calculation of steam thermodynamic properties and a computer-aided search of steam enthalpy-entropy diagram. Through the use of two-phase flow theory and compressible fluid thermodynamic principles the problem of steam and cooling water mixed flow multi-stage multi-orifice throttling can be transformed into a problem of iterative root extraction of a nonlinear equation. The above makes it possible to perform a computer-aided analysis of the thermodynamic properties of a pressure and temperature reduction device for a steam turbine bypass system. **Key words**: steam turbine, bypass system, pressure and temperature reduction device, thermodynamic properties, computer-aided analysis

汽泡生长诱导的速度场= **An Induced Velocity Field of Steam Bubble Growth**[刊,中]/Gu Pingdao, Lu Changgen(Jiangsu Petrochemical Institute) //Journal fo Engineering for Thermal Energy & Power. - 1997, 12(5). - 374~376

With the help of Apollonius conformal transformation and Fourier series method obtained is an induced velocity field of steam bubble growth process in a stationary flow field. **Key words**: steam bubble expansion, induced velocity field, conformal transformation, expansion circle

含不凝气体的蒸汽冷凝换热系数的关联式= **A Correlation of Condensation Heat Exchange Factor of Steam Containing Non-condensable Gases**[刊,中]/Xiong Mengquing, Lin Zonghu(Xi'an Jiaotong University), Liu Shengding(Xi'an Architectural University of Science & Technology) //Journal of Engineering for Thermal Energy & Power. - 1997, 12(5). - 377~380

The authors have established a heat exchange model for condensation heat exchange of steam-containing non-condensable gases. By using the said model and numerous heat exchange data a correlation for factor of condensation heat exchange between air-containing steam and the outer surface of a horizontal smooth round tube is obtained, which has practical engineering applications and is easy to use. **Key words**: mixed gases, conden-

?1994-2018 China Academic Journal Electronic Publishing House. All rights reserved. http://www