变比热不可逆气动参数解析解

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[摘要]本文依据文献〔1〕给出的烃燃气热力性质计算方法,计算了热力学状态参数。在计算气动参数时,引入不可逆的概念。编写了求解燃气热力学参数的通用程序。程序适用于燃料系数 β 从0到1;温度从200 K到1800 K范围的任意碳氢比的烃燃料燃烧后生成的燃气。气动参数的结果与文献〔2〕多比热结果进行了比较,其差别在0.1%以内。计算程序求解合理而且方便,可在工程设计中应用。

关健词　变比热　不可逆　热物性　解析解
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1 引言

随着电子计算机的发展,计算机体力学也得到了飞速的发展,人们对计算结果的精度以及计算结果的可信度要求越来越高。在热机的循环分析、部件性能分析以及气动力设计计算的科研工作中,由于膨胀或压缩导致大的压力梯度和温度梯度,同时还存在着各种损失因素,使工质在流动过程中,状态参数发生很大的变化,采用定比热参数的计算方法使结果产生较大的误差,设计结果不能达到预期的要求,更有甚者,当热力状态参数有一微小变化,有可能造成得不到一个收敛解。因此,寻找一种合理的变比热不定熵的热力气动参数的计算方法具有十分重要的意义。

以往多数气动设计者,在计算流场的性能参数时,大都采用定比热。分段定比热或多比热方法,如文献〔2〕。这些计算分析方法在工程设计分析中起了相当大的作用。而当代发动机中气流速度大,各部件之间的温度差也大。因此采用平均比热的观点,正如文献3中所说,很显然会产生较大的计算误差,在涡轮部件中,这种差异尤其显著。

典型燃料 C_8H_{16} 燃烧生成的燃气的热力性质,可由燃气性质表4查得,但它不适合计算机计算,而且精度较低。文献〔1〕给出了改进的热物性质表,并给出了压力修正项和参数拟合系数。以此为基础,我们编写了求解热力参数和气动参数的计算机实用程序。通过对文献〔2〕、〔3〕中的算例进行验算,结果表明,本程序的完全变比热方法与文献〔2〕的多比热计算结果误差在0.1%以内。与文献〔3〕的结果差异较大,其原因可能由于采用了不同的热物性质造成。

本文的指导思想是在热力气动性质参数计算中,对于给定组成的完全气体,定压比热、比热比以及焓值等参数均只是温度的单的单值函数。而在气体流动过程中引入熵增,得出了一组计算变比热不等熵的气动参数计

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算公式。

2 热力学关系式

在燃气轮机中工作的工质，不论是压气机中的空气，还是燃烧室和涡轮中的燃气，均可认为是处在压力不很低，温度不很高的状态下，即可将其视为理想气体。因此其参数满足状态方程：

$$P = R\rho T \tag{1a}$$

$$\text{或} \quad p^* = R\rho^* T^* \tag{1b}$$

其中上标 * 代表滞止参数。假设状态参数焓和定压比热均只是温度的单值函数，可用表达式表示：

$$C_p = f_1(T) \tag{2}$$

$$dh = C_P dT \tag{3a}$$

$$\text{或} \quad h_2 - h_1 = \int_{T_1}^{T_2} C_P dT \tag{3b}$$

任意一状态静参数同其对应的滞止参数之间可认为是等熵变化。则下列关系式成立：

$$\frac{P}{P^*} = \frac{\pi_T^0}{\pi_{T^*}^0} \tag{4}$$

其中 $\pi_T^0, \pi_{T^*}^0$ 为相对压力。

根据热力学第二定律：

$$Tds = dh - vdp \tag{5a}$$

$$\text{或} \quad ds = \frac{1}{T}dh - \frac{R}{P}dp \tag{5b}$$

将(3a) 代入(5b) 得：

$$ds = \frac{C_P}{T}dT - \frac{R}{P}dp \tag{6a}$$

$$\text{或} \quad S_2 - S_1 = \int_{T_1}^{T_2} \frac{C_P}{T}dT - R\ln(\frac{P_2}{P_1}) \tag{6b}$$

其中 R 为气体常数，它只与气体组分有关。而静参数同滞止参数之间有关系：

$$\ln(\frac{P^*}{P}) = \int_{T}^{T^*} \frac{C_P}{RT}dT \tag{7}$$

由式(7) 可以看出，相对压力只是温度的单值函数。

当已知静参数 P. T 和总参数 P^*，则可求出总温 T^*。即只需知道三个独立参数，则其他参数均可唯一的确定。

对于任意氢碳比为 n 的燃料，生成燃料系数为 β 的燃气，其热力性质可采用文献 1 的方法求得。

3 气动参数关系式

在压力机和涡轮部件气动计算中，气体参数变化过程可以认为是绝热的，即忽略其与外界的热交换。根据热力学第一定律，总焓与静焓有关系式：

$$h^* = h + \frac{1}{2}V^2 \tag{8a}$$

由(3b)，我们可将上式改写成：

$$\int_{T}^{T^*} C_P dT = \frac{1}{2}V^2 \tag{8b}$$

假设气体流动过程中，摩擦力作的功全部转化成气体的内能，即气体的总焓不变。

$$h_1^* = h_2^* \tag{9}$$

将式(8b) 代入(9) 中则：

$$\int_{T_1}^{T_2} C_P dT = \frac{1}{2}V_1^2[1 - (\frac{V_2}{V})^2] \tag{10}$$

式(10)即为能量方程。

另外我们可以将连续方程和状态方程写成如下关系：

$$\frac{P_1}{P_2} = \frac{T_1}{T_2} \cdot \frac{V_1}{V_2} \tag{11a}$$

$$\text{或} \quad \frac{V_2}{V_1} = \frac{T_1}{T_2} \cdot \frac{P_2}{P_1} \tag{11b}$$

将式(11b) 代入能量方程(10)，得：

$$\int_{T_1}^{T_2} C_P dT = \frac{V_1^2}{2}[1 - (\frac{T_1}{T_2})^2(\frac{P_2}{P_1})^2] \tag{12}$$

当已知初始状态参数 p_1, T_1, P_1^*，可由式(7) 求出总温 T_1^*，由式(8b)，求出初始状态的速度 V_1。

当给定两状态的压比 P_2/P_1 时，则可由式〈12〉通过迭代求出 T_2。则状态 2 的热力参

数和气动参数速度 V_2 就全可由上述公式求得。

从初始状态 1 到状态 2，熵增值可由式(6b)求得，或通过下式计算：

$$\Delta S = -R\ln(P_2^*/P_1^*) \tag{13}$$

其中 $P_2^*/P_1^* = \delta$，称为总压恢复系数。

而：$$P_2^* = P_2\pi^0_{T_1^*}/\pi^0_{T_2} \tag{14}$$

由上述各关系式，我们可以求得任意流动过程中，气体热力参数和气动参数。

计算值的准确性如何，我们可以通过比较压力恢复系数的理论值和试验的结果来验证。

4　算例

众所周知，常用到的热力气动参数有 h，S、T、ρ、P、T、M、a、V 等，对上述参数可分为状态参数和过程参数两大类。而对状态参数来说，确定一个状态，只须知道两个参数，其它状态参数就可以唯一的确定。两个状态之间是通过过程参数联系起来的。气体流动过程中满足能量守恒和质量守恒。我们对文献〔2〕、〔3〕中算例的部分参数进行了验算，其结果对比见表 1 和表 2。

表 1　**新旧热力性质计算结果对照**

	空气定熵压缩，$T_1=100℃$，$T_2=500℃$						燃气 $\beta=1$，定熵膨胀，$T_1=500℃$，$T_2=100℃$					
	旧热力性质			新热力性质			旧热力性质			新热力性质		
	k	P_2/P_1	误差 %	k	P_2/P_1	误差 %	k	P_1/P_2	误差 %	k	P_1/P_2	误差 %
k_a	1.397	12.98	−7.7	1.3970	12.9830	−8.41	1.315	20.93	+20.2	1.3151	20.9081	+17.39
$\bar{k}_b$	1.377	14.31	+1.7	1.3767	14.3306	+1.09	1.339	17.77	+2.1	1.3393	17.7391	−0.4
$\bar{k}_c$	1.379	14.16	+0.6	1.3788	14.1785	+0.02	1.335	18.23	+4.7	1.3390	17.7667	−0.24
$\bar{k}_d$	1.378	14.22	+1.1	1.3764	14.3508	+1.24	1.339	17.78	+2.1	1.3363	18.0769	+1.5
$\bar{k}$	1.380	14.07	0		14.1757	0	1.342	17.41	0		17.8102	0
	空气定熵压缩，$T_1=200℃$，$T_2=1000℃$						燃气 $\beta=1$，定熵膨胀，$T_1=1000℃$，$T_2=200℃$					
$\bar{k}_a$	1.389	34.28	−22.0	1.3892	34.2329	−22.52	1.277	95.90	+52.1	1.2771	95.7949	+48.73
$\bar{k}_b$	1.354	43.94	0	1.3545	43.9073	−0.62	1.314	62.94	−0.2	1.3143	62.7576	−2.56
$\bar{k}_c$	1.347	46.64	+6.1	1.3466	46.7747	+5.87	1.305	69.08	+9.6	1.3050	69.0520	+7.21
$\bar{k}_d$	1.348	46.26	+5.3	1.3479	46.2947	+4.78	1.308	67.21	+6.6	1.3059	68.3933	+6.19
$\bar{k}$	1.354	43.96	0		44.1814	0	1.314	63.05	0		64.4094	0

注：k_a、k_b、$\bar{k}_c$、$\bar{k}_d$、$\bar{k}$ 定义同文献〔3〕

5　结论

通过上述算例结果的对比，我们可以得出如下几点结论：

1　不同的定比热计算方法，计算结果存在着很大区别。变比热计算虽然显得比较繁琐，但是在温度变化比较大的情况下，必须采用变比热计算。由于计算机速度的提高，变比

表 2　变比热气动参数解析解与准确解对比

	$T^* = 800\,k, P^*/P = 10, g_r = 0.015$			$T^* = 1800\,k, P^*/P = 10, g_r = 0.055$		
	解析解	准确解 $k_k = 1.3561$ $k_v = 1.3494$ $k = 1.3632$ $\bar{k} = 1.3657$ $\bar{k}_v = 1.3500$	次精确解 $k_k = 1.3561$ $k_v = 1.3494$ $k = 1.3632$	解析解	准确解 $k_k = 1.2706$ $k_v = 1.2675$ $k = 1.2766$ $\bar{k} = 1.2785$ $\bar{k}_v = 1.2683$	次精确解 $k_k = 1.2706$ $k_v = 1.2675$ $k = 1.2766$
$\tau(\lambda)$	0.539 843 7	0.5398 − 0.0081%	0.5415 0.3068%	0.605 468 8	0.6055 0.0052%	0.6073 0.3024%
λ	1.730 469	1.7306 0.0076%	1.7274 − 0.1777%	1.801 419	1.8028 0.0767%	1.7990 − 0.1343%
C	890.848 9	890.58 − 0.0302%	888.94 − 0.2143%	1 371.945 0	1371.39 − 0.0405%	1368.52 − 0.2496%

热计算所占用 CPU 的时间比起复杂的矩阵求解来说是微不足道的。

2　在精度要求不太高的工程问题中，文献〔2〕中的次精确解是可信的。其准确解的精度同本文完全变比热的解析解精度相当，误差在 0.1%以内。

3　文献〔3〕中的算例，本人采用相同的求解方法得出的结果与其存在着比较大的差别，其主要原因在于所用的热物性依据不同。文献〔3〕采用的是文献〔4〕的数据。本文采用的是文献〔1〕的数据，更接近真实的热物性值，其数据更合理，精度更高。

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WR21 中冷回热燃机的点火试验

据《Gas Turbine World》1994 年 3—4 月号报道，针对美国海军先进水面舰艇机械计划，美国西屋公司和英国罗尔斯一罗伊斯公司联合研制的第一台 WR21 燃气轮机按预定计划将在 1994 年 7 月点火试验。

以馏出油作为燃料，WR21 的额定功率为 19417 kW(20400 hp)，具有与 DDG—51 型伯克级导弹驱逐舰装用的简单循环 LM2500 发动机相同的底座，并能使军舰的燃料消耗减少 30%以上。通过 23 个月的努力，研制小组已设计了燃气轮机的全部部件并完成了大多数模型和部件的试验。

在有关的报道中，美国海军防务采购部已允诺把该发动机作为 1996 年财政年度中第二批 DDG—51 型导弹驱逐舰预约装备的候选机组。

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flow as well as horizontal tube diameter on the operating performance of the pneumatically controlled L valve slag removal mechanism. **Key Words**: *pressurized fluidized bed boiler, slag removal mechanism pneumatic control*

△**An Experimental Study of Embedded Tube Heat Transfer and Heat Resistance Control in a High-temperature Fluidized Bed**……Yan Weiping. (*North China Institute of Electric Power*) **Journal of Engineering for Thermal Energy & Power**, 1995, 10(1): 25～30

Presented and analysed in this paper is the surface temperature of a horizontally embedded tube in a high-temperature fluidized bed and the experimental result regarding the effect of power bed material on the embedded tube outer side heat transfer coefficient. It has been shown that the heat transfer factor is closely related to the surface temperature, but the degree of correlation depends on the particle diameter and sieve range adopted. The adding of powder bed material will lead to an increase in heat transfer coefficient, but the degree of increase is also related to the controlled heat resistance. **Key words**: *high-temperature fluidized bed, embedded·tube heat transfer coefficient, surface temperature, particle diameter*

△**The Effect of Tertiary Air on In-furnace Thermal Load Distribution**……Guo Hongsheng, Xu Tongmo (*Xi' an Jiaotong University*) **Journal of Engineering for Thermal Energy & Power**, 1995, 10(1): 31～35

An experimental study has been conducted of the thermal load distribution in a tangentially fired boiler furnace with burners installed at the four corners of the boiler. The variation of the thermal load distribution is compared for cases with or without the use of tertiary air. With the help of a self-made radiation type heat-flux meter the test has been performed on a small-size hot-state simulation test rig with lean coal of Tongchuan serving as the test fuel. The tset resuits have shown that the injection of tertiary air can lead to a quickening of the damping tempo of the infurnace thermal load along the furnace height. **Key words**: *radiation heat transfer, combustion*

△**The Study and Application of Self-forming Type Coal for Industrial Boilers**……Hui Shi' en (*Xi' an Jiaotong University*) **Journal of Engineering for Thermal Energy & Power**, 1995, 10(1): 36～40

With a view to solving the problem of an increasing amount of fine coal dust, fly ash and unburned coal siftings loss and serious atmospheric pollution the author has proposed the fabrication of a type of self-forming coal and its combustion mode. As a result of a great deal of experimental investigations the main factors affecting the self-forming coal without binding agents have been ascertained. The said coal has found wide applications in industrial production and undergone further experimental verification in its practical use. **Key words**: *industrial boiler, self-forming coal, study*

△**Some Comments on the Feedwater Deaeration of Small-sized Industrial Boilers**……Gao Yang (*Beijing Petro-Chemical Engineering Co*) **Journal of Engineering for Thermal Energy & Power**, 1995, 10(1): 41～44 **Key words**: boiler, deaeration, thermal deaeration

△**An Analytical Solution of Irreversilbe Aerodynamic Parameters of Variable Specific Heat**……Yu Qing, et al. (*Harbin Institute of Technology*) **Journal of Engineering for Thermal Energy & Power**, 1995, 10(1): 45～48

Based on the calculation method given in Reference [1] for hydrocarbon gas thermodynamic properties the author has calculated the thermodynamic state parameters. An irreversibility conception is introduced during the calculation of such parameters. A general program for solving gas thermodynamic parameters has been drawn up, which is suitable for gases generated as a result of the combustion of hydrocarbon fuels of arbitrary hydrocarbon ratio with fuel factor β ranging from 0-1 and temperature ranging from 200 k to 1800 K. The aerodynamic parameters obtained have been compared with the multiple specific heat results given in Reference [2] and the difference is found to be within 0.1%. The calculation progran features a rational solution and ease of application, making it suitable for use in various engineering designs. **Key words**: variable specific heat, irreversible thermophysical properties, analytical solution

△**The reliability Analysis of Single Disk Rotor Vibrations**……Xu Zili(*Harbin Institute of Technology*) **Journal of Engineering for Thermal Energy & Power**, 1995,10(1):49～52

Described in this paper is a calculation formula for a single disk rotor system vibration response. A reliability safe margin equation of the rotor corresponding to a vibration failure mode has been deduced and the vibration reliability calculation methematical model for the single disk rotor system established. This paper also discusses the effect of the variation of various parameters on the rotor vibration reliability and gives a calculation example to illustrate the applicabillty of the above-cited method. **Key words**: *single disk rotor*, *reliability*

△**A New Type of Thermal Insulation Material with a Reflective Multi-layer Thermal Insulation Structure**……Xiong Yangheng (*Wuhan University of Electric Power Engineering & Water Resources*)**Journal of Engineering for Thermal Energy & Power**, 1995,10(1):53～56

On the basis of the author' s earlier work the thermal insulation performance of a reflective multi-layer insulation structure was analysed and calculated during its use in a variety of conditions. The technico-economic performance of the new structure is compared to that of other conventional thermal insulation materials. The results of comparison show that the new thermal insulation structure features a better comprehensive technico-economic performance **Key words**: *thermal insulation*, *reflective multi-layer structure of thermal insulation*, *technico-economic performance*, *critical heat insulation layer number*

△**The Failure Analysis of a Boiler Lower Header**……Wu Qingyu, et al. (*Boiler & Pressure Vessel Inspection Institution under the Harbin Labor Bureau*)**Journal of Engineering for Thermal Energy & Power**. 1995, 10(1):57～60

A multitude of ring-shaped cracks and three water leakage points were discovered in the right side lower header of a boiler together with a cave-in of the boiler roof water-cooled wall. Through the metallographic analysis of the materials used for the left and right side lower header and the said water-cooled wall as well as an analysis of the boiler construction and water circulation circuits the cause of the boiler lower header failure was finally identified. **Key words**: *boiler*, *lower header*, *metallographic structure*, *failure analysis*