

# 符合水蒸气新骨架表的蒸汽压方程

李志旺 苏志军

严家骝

(黑龙江省电力试验研究所) (哈尔滨工业大学)

〔摘要〕 本文提出了一个温度范围从三相点到临界点的水的蒸汽压方程。计算值全部落在1985年公布的国际水蒸气骨架表的允差范围以内。

关键词 水蒸气 骨架表 蒸汽压

## 1 前言

水的蒸汽压数据在热动力工程中是重要的基本数据,它的精度高低直接影响着流体热力性质计算数据的真实性。1985年,国际水蒸气协会公布了最新的水蒸气骨架表<sup>[1]</sup>并同时废除了1963年公布的骨架表<sup>[2,3,4]</sup>。新水蒸气骨架表温度范围没有变动,但压力范围提高到1 000 MPa,而且对水的热力性质参数的精度要求更高,允差范围要求更小。为编制符合新骨架表的水蒸气热力性质表,填补国内这方面的空白,本文先提出一个水的蒸汽压方程。

## 2 方程的提出

由热力学可知,克拉伯龙方程有如下形式:

$$\begin{aligned} \frac{dp_s}{dT_s} &= \frac{r}{T_s(v'' - v')} \\ &= \frac{r}{T_s(z'' - z') \frac{RT_s}{p_s}} \end{aligned}$$

亦即

$$\frac{dp_s}{p_s} = \frac{r}{R(z'' - z')} \frac{dT_s}{T_s^2} \quad (1)$$

令:

$$\begin{aligned} \frac{r}{R(z'' - z')} &= C_1 + C_2 T_s + C_3 T_s^2 \\ &+ \dots + C_K T_s^{K-1} + C_m T_s^m \end{aligned} \quad (2)$$

式中 $m$ 是正实数。将式(2)代入式(1)并积分得:

$$\begin{aligned} \ln p_s &= C_0 - \frac{C_1}{T_s} + C_2 \ln T_s + C_3 T_s \\ &+ \frac{C_4}{2} T_s^2 + \dots + \frac{C_K}{K-2} T_s^{K-2} \\ &+ \frac{C_m}{m-1} T_s^{m-1} \end{aligned}$$

或写成:

$$\begin{aligned} \ln p_s &= D_1 + D_2/T' + D_3 \ln T' \\ &+ D_4 T' + D_5 T'^2 + D_6 T'^3 \\ &+ \dots + D_{K+3} T'^K + D_q T'^q \end{aligned} \quad (3)$$

这里  $T' = T_s/100$ ,  $K$  是正整数,  $q$  是正实数。 $D_1, D_2, \dots, D_{K-3}, D_q$  是方程的常数,它们可由饱和蒸汽压实验数据回归求得。对不同的物质,蒸汽压方程有不同的常

数。

允差范围以内，限于本文篇幅，附表中列出了水的蒸汽压的部分计算结果。

### 3 水的蒸汽压方程常数的确定

表 1 水蒸汽压计算值与骨架表<sup>[1]</sup>值比较

国际水蒸气骨架表中规定在  $T_0 = 373.15 \text{ K}$  时，饱和压力  $p_0 = 0.101 325 \text{ MPa}$  不允许有误差，因此有

$$\ln p_0 = D_1 + D_2/T_0' + D_3 \ln T_0' + D_4 T_0' + D_5 T_0'^2 + D_6 T_0'^3 + \dots + D_{K+3} T_0'^K + D_q T_0'^q \quad (4)$$

式中  $T_0' = 3.731 5$ ，由式 (4) 求得

$$D_1 = \ln p_0 - D_2/T_0' - D_3 \ln T_0' - D_4 T_0' - D_5 T_0'^2 - D_6 T_0'^3 - \dots - D_{K+3} T_0'^{K+3} - D_q T_0'^q \quad (5)$$

这就是说，常数  $D_1$  可用其它常数来表示。将式 (5) 代入式 (3) 中，用1985年国际水蒸气骨架表中饱和蒸汽压的数据<sup>[1]</sup>，按最小二乘法原理进行非线性回归，同时按目标函数：

$$O.F = \sum_{i=1}^n \left\{ \frac{p_{\text{计算}} - p_{\text{表}}}{p_{\text{表}}} \right\}^2 \rightarrow \text{最小}$$

调节  $q$  值，由微机求得方程的常数如下：

$D_1 = 16.651 299$ ,  $D_2 = -53.865 285 7$ ,  
 $D_3 = 12.481 523 7$ ,  $D_4 = -8.172 158 2$ ,  
 $D_5 = 0.869 589 1$ ,  $D_6 = -5.740 154 5 \times 10^{-2}$   
 $D_7 = D_8 = \dots = D_{K+2} = 0$ ,  $D_{K+3} = 4.335 209 8 \times 10^{-21}$ ,  
 $D_q = 2.868 622 3 \times 10^{-3}$ ,  $K = 23$ ,  
 $q = 3.8$ ,  $AAD = 0.03\%$  所以水的蒸汽压方程可描述为：

$$\ln p_s = 16.651 299 - 53.865 285 7/T' + 12.481 523 7/nT' - 8.172 158 2T' + 0.869 589 1T'^2 - 5.740 154 5 \times 10^{-2}T'^3 + 4.335 209 8 \times 10^{-21}T'^{23} + 2.8686223 \times 10^{-3}T'^{3.8} \quad (6)$$

由于式中含有  $T$  的高次幂，为使计算机计算式 (6) 时不溢出，这里采用  $T' = T_s/100$  作为自变量。用式 (6) 求得的水的蒸汽压数值全部落在1985年国际水蒸气骨架表的

温度 (K)	骨架表 <sup>[1]</sup> 中压力 (MPa)	允差 <sup>[1]</sup>	计算压力 (MPa)
273.16	0.000 611 659	±0.000 000 010	0.000 611 660
283.15	0.001 227 92	0.000 000 09	0.001 227 92
293.15	0.002 338 49	0.000 000 29	0.002 338 54
303.15	0.004 245 1	0.000 000 6	0.004 245 2
313.15	0.007 381 1	0.000 001 0	0.007 381 1
323.15	0.012 344 6	0.000 001 5	0.012 344 4
333.15	0.019 933 1	0.000 002 1	0.019 932 7
343.15	0.031 177 7	0.000 002 8	0.031 177 0
353.15	0.047 375 9	0.000 003 8	0.047 375 1
363.15	0.070 121	0.000 005	0.070 120
373.15	0.101 325		0.101 325
393.15	0.198 48	0.000 05	0.198 49
403.15	0.270 02	0.000 07	0.270 02
423.15	0.475 71	0.000 12	0.475 72
443.15	0.791 47	0.000 20	0.791 46
463.15	1.254 17	0.000 30	1.254 14
483.15	1.906 2	0.000 5	1.906 1
503.15	2.795 0	0.000 7	2.795 0
523.15	3.973 5	0.001 0	3.973 6
543.15	5.499 6	0.001 4	5.499 8
563.15	7.437 5	0.001 8	7.437 8
583.15	9.859 7	0.002 5	9.859 5
603.15	12.851 5	0.003 2	12.850 3
623.15	16.521	0.004	16.521
643.15	21.033	0.005	21.036
644.15	21.286	0.005	21.288
645.15	21.542	0.005	21.543
646.15	21.802	0.005	21.801
647.15	22.064	0.005	22.059

注：表中允差值除第一行前面标有“±”外，以下各允差值前面的“±”号均省略。

### 4 结论

本文提出的水的蒸汽压方程精度高，从水的三相点到临界点，蒸汽压计算值全部落在1985年国际水蒸气骨架表的允差范围之

内,为科学和工程计算以及编制新的高精度的水蒸气热力性质表提供了准确的蒸汽压计算公式。

### 符号说明

$p_s$ ——饱和蒸汽压力, MPa。

$T_s$ ——饱和蒸汽温度, K。

$z''$ 、 $z'$ ——饱和蒸汽、饱和水的压缩因子。

$r$ ——汽化潜热, kJ/kg。

$R$ ——气体常数, kJ/(kg·K)。

$AAD$ ——绝对平均偏差, %,  $AAD =$

$$\frac{1}{n} \sum_{i=1}^n \frac{|p_{计} - p_{表}|}{p_{表}} \times 100\%$$

tables 1985 for the thermodynamic properties of ordinary water substance. Unrestricted publication allowed in all countries. 1985.11.18.

2 斯米特 E 等. 国际单位制的水和水蒸气性质. 赵兆颐译. 北京: 水利电力出版社, 1983

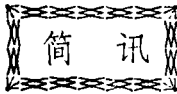
3 Vargaftik N B. Tables on the thermophysical properties of liquids and gases in normal and dissociated states. Hemisphere Pub. Corp., 1975

4 Reynolds W C. Thermodynamic properties IN SI. Dep. Mech. Eng., Stanford University. 1979.

### 参考文献

1 The IAPS. Release on the IAPS skeleton

(李乡复 编辑)



## 研制高效率燃机

据“Gas Turbine World”1992年1—2月号报道,美国涡轮动力和船用分部正在研制FT4000型燃气轮机。该机是PW4000型商用航空涡轮风扇发动机的工业改型,拟在1995年左右用于电力生产、机械传动和船舶推进。

在ISO条件下燃用天然气,该发动机基本负荷额定功率为45 MW,基本负荷涡轮进口温度为1251℃,简单循环热效率将高达43%,这将是迄今为止简单循环燃气轮机的最高效率。

## 压气机的防腐涂层

据“ASME Journal of Engineering for Gas Turbines and Power”1991年10月号报道,为了延长维修间隔并改进安装在运输和海上巡逻飞机上的涡轮螺旋桨发动机的性能,加拿大国防部正对应用在压气机上的防磨蚀和腐蚀的叶片涂层进行评定。

近年来,现代化的叶片涂层技术已取得了很大进展。除了能防磨蚀和防腐蚀外,还要求新型的“超光滑”涂层能明显改进气动性能。进行评估的压气机叶片涂层是氮化钛涂层,涂层的平均厚度约为6—8微米。最值得注意的涂层影响是对修正的空气流量、压气机压比和燃烧室压比等参数的影响。而用户最关心的性能参数是输出功率和耗油率。

(吉桂明 供稿)

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An Experimental Study of the Optimization of  
Flow Resistance Characteristics at the Exhaust  
Pipe Inlet (Provided with a crossbar) of a Cyclone  
Separator with No Internal Swirling Flow

Wang Rong, Wang Huaibin and Zhang Zidong  
(Harbin Institute of Technology)

He Weicai

(Energy Saving Center of Guangdong province)

Abstract

Resistance loss caused by internal swirling flows accounts for more than 50% of a cyclone separator total resistance loss. Due to the absence of internal swirling flows in a cyclone separator with no internal swirling flows it is possible to significantly lower flow resistance loss. With the addition of a crossbar at the exhaust pipe inlet of a cyclone separator the rotation speed of clean gas flow can be reduced, thus effecting a decrease of resistance loss by one third. Based on test results, this paper makes an optimization study of the resistance characteristics at the inlet (with a crossbar being added) of such a cyclone separator.

**Key words:** cyclone separator, internal swirling flow, crossbar, resistance characteristics

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Vapor pressure Equation which complies with a  
New Skeleton Table of Water Vapor

Li Zhiwang and Su Zhijun

(Heilongjiang Electric Power Test Institute)

Yan Jialu

(Harbin Institute of Technology)

Abstract

In this paper is presented a water vapor pressure equation with a temper-  
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ature range from three-phase point up to a critical point. All the calculation values fall under the allowance range of the international water vapor skeleton table published in 1985.

**Key words:** *water vapor, skeleton table, steam pressure*

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## Main Powerplants for Current Surface Fighting Ships

Ji Guiming

*(Harbin Marine Boiler & Turbine Research Institute)*

### Abstract

This paper describes the present situation of main propulsion plants installed on commissioned aircraft carriers, cruisers, destroyers and frigates, and based on available statistics makes an analysis of the use of various power plants on the above-cited warships for the last thirty years. The development tendency of such propulsion plants for various types of naval vessels is also indicated.

**Key words:** *aircraft carrier, cruiser, destroyer, frigate, main propulsion plant, technical overview*

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