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300 ~3 000 K 水蒸气红外辐射谱带模型参数

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摘　要：水蒸气分子光谱数据在航天科学、大气科学、天体物理以及热能动力工程中有着广泛的应用。本文以最新的高分辨率高温燃气光谱数据库 HITEMP 为基础，通过合理的外推，计算得到 300～3 000 K 的温度范围内水蒸气谱带模型参数：平均吸收系数、谱线密度、谱线半宽，建立了比 1973 年 NASA 发布的数据更新、更详细的模型参数表。以本文的模型参数表为基础，采用统计谱带模型计算了各种光学路径下的发射光谱，其结果与实验值符合很好。

关　键　词：红外辐射；水蒸气；谱带模型参数

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1　前言

水蒸气是高速飞行器尾喷焰红外辐射的主要成分，也是影响大气背景红外辐射传输的主要气体，同时还是工业炉炉膛，燃气轮机燃烧室以及化学工业反应炉内主要燃烧产物。其辐射特性光谱数据多年来国外已经从理论和实验上进行了深入研究，但在一些文献中只给出了低温下的少量数据，覆盖的温度区间、光谱区间不全，分辨率较低，而且有些数据精度尚不够，对于目前开展的高速飞行目标、背景红外辐射和传输特性等方面的研究是不够的。航天科学和工程研究迫切需要大量水蒸气分子光谱数据。自 70 年代以来，美国空军地球物理实验室就致力于高分辨率气体分子光谱参数数据库 HITRAN[1] 的建设，发表了不同版本，但 HITRAN 数据库仅包括少量的“热线”参数，一般适用于较低温度(小于 800 K)，如大气背景辐射传输计算；在火箭、飞机尾喷焰等高温场合，分子光谱将会有大量的“热线”出现，HITRAN 数据库已经不适用。所以在 HITRAN 数据库的基础上 HITRAN 的作者们在 90 年代末期又发展出水蒸气、二氧化碳及一氧化碳的高温燃气高分辨率谱线光谱参数数据库 HITEMP，并出版了其光盘版。HITEMP 中包括超过 70 万条水蒸气的谱线参数，这样大的数据库使用起来非常不方便，计算费时。因此需要一套简单，同时还能把气体分子的光谱特点描述得足够细致、准确的光谱数据，即谱带模型参数数据。

本文在 HITEMP 基础上计算得到水蒸气全光谱区间、大温度范围内的谱带模型参数：平均吸收系数 $\bar{k}$，谱线密度 $1/\bar{d}$ 和平均半宽 $\bar{\gamma}$。另文中将给出二氧化碳、一氧化碳的谱带模型参数。可联合应用于高速飞行器尾喷焰红外辐射、红外背景辐射传输以及高温燃烧室内热辐射换热计算。

2　理论方法

光谱学理论研究表明准确的描述一个气体的谱带需要三个参数，即平均吸收系数 $\bar{k}$，谱线密度（谱线平均间距的倒数）$1/\bar{d}$ 和谱线平均半宽 $\bar{\gamma}$。

考虑到水蒸气谱带内谱线数目非常巨大，所以可以假设在谱带内谱线位置是随机分布的，谱线强度符合统计强度分布规律。如用双参数指数尾倒数的谱线强度分布描述气体谱带，在某一波数 w 附近 $[w-\Delta w/2, w+\Delta w/2]$ 区间内的平均穿透率 $\overline{\tau_w}$ 可由下式给出：

$$\overline{\tau_w} = \exp\left[-2\bar{\gamma}/\bar{d}\left(\sqrt{1+u\bar{k}\bar{d}/\bar{\gamma}}-1\right)\right] \qquad (1)$$

式中：$u = P_{H_2O}L(296/T)$，标准化到 0.101 MPa，296 K 的压力行程；P_{H_2O}－气体分压力；L－行程长度。

本文是以 HITEMP 数据库为基础计算谱带模型参数，因此采用了 S.J.Young[2] 提出的算法。此算法简单可靠，适合于详细的谱线光谱参数数据是已知的情况下计算谱带模型参数。其公式如下：

$$\bar{k} = \frac{1}{\Delta w}\sum_{m=1}^{M} S_{w_0 m},\ \bar{\gamma} = \frac{1}{M}\sum_{m=1}^{M}\gamma_m,$$

$$\frac{1}{\bar{d}} = \left(\frac{1}{\Delta w}\sum_{m=1}^{M}\sqrt{S_{w_0 m}\gamma_m}\right)^2 / \bar{k}\bar{\gamma} \qquad (2)$$

式中：$S_{w_0 m}$ 为 Δw 内第 m 条谱线积分强度；γ_m 是 Δw

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内谱线的半宽；M 是 Δw 内谱线总数；$\bar{k}$ 单位是 1/(cm.MPa)；γ 单位是 1/cm；$1/\bar{d}$ 单位是 cm。

2.1　高温下 $S_{w_0 m}$ 的计算

HITEMP 数据库中的光谱参数都是标准态 0.101 MPa、296 K 下的，其他压力、温度下需要经过合理的理论外推。由原子、分子辐射吸收理论可知谱线的积分强度 $S(T)$[4]（对于一个原子或分子来讲）是仅与温度有关的量：

$$S(T) = [(8\pi^3 10^{-36})/(3hc)][I_a/(g_j Q_V(T) Q_R(T))] \times w_0 \times \exp(-G''_V/kT) \times \exp(-E''_R/kT)[1-\exp(-hcw_0/kT)] |R_V|^2 L(J'', l) F(J'') \tag{3}$$

式中：h—Planck 常数；c—光速；I_a—同位素丰度；w_0—谱线位置；E''_R—低态转动能；k—Boltzmann 常数；g_j—统计权重；$|R_V|^2$—振动态跃迁矩阵元；$L(J'', l)$—Hönl—London 因子；G''_V—振动谱项(能量)；$Q_V(T)$，$Q_R(T)$—振动转动配分函数；$F(J'')$—Herman—Wallis 因子。

由此可得标准状态(0.11 MPa、296 K) 下的谱线强度值

$$S_0(T_0) = [(8\pi^3 10^{-36})/(3hc)][I_a/(g_j Q_V(T_0) Q_R(T_0)) w_0 \times \exp(-G''_V/kT_0) \times \exp(-E''_R/kT_0)[1-\exp(-hcw_0/kT_0)] |R_V|^2 \times L(J'', l) F(J'') \tag{4}$$

公式(3) 和(4) 中的 $|R_V|^2 L(J'', l) F(J'')$ 跃迁矩阵元项是只与能态(频率、波长) 相关的量而与温度无关。式(3) 除以式(4)，并假设在计算区间气体都可按理想气体处理，那么气体的分子数密度是温度和压力的函数 $N(P, T) = NL(T_0/T)(P/P_0)$，可得到强度表达式：

$$S(T) = S_0(T_0) NL \left(\frac{T_0}{T}\right) \left(\frac{P}{P_0}\right) \frac{Q_V(T_0) Q_R(T_0)}{Q_V(T) Q_R(T)} \exp\left(-\frac{E''}{k}\left(\frac{1}{T}-\frac{1}{T_0}\right)\right) \times \frac{[1-\exp(-hcw_0/kT)]}{[1-\exp(-hcw_0/kT_0)]} \tag{5}$$

式中：

NL——296 K，0.11 MPa 单位体积(cm^3) 内的分子数，$NL = 2.479 \times 10^{19}$，$1/\mathrm{cm}^3$；

这样由 HTEMP 数据库当中的谱线强度(单个分子的) 可推得其它温度压力下的谱线强度。

2.2　谱线半宽 γ_m 的计算

HITEMP 数据库中给出了空气增宽(即认为外增宽气体为空气) 和自增宽半宽，同样也是标准化到 $T_0 = 296$ K，$P_0 = 0.1$ MPa，同理，其他温度、压力下，可以外推得到[1]：

$$\gamma_m(P, T) = \gamma_m^0 (T_0/T)^n (P/P_0) \tag{6}$$

式中：γ_m^0 由 HITEMP 中两部分组成：自增宽半宽 $\gamma_{m,\mathrm{self}}^0$ 和空气增宽半宽 $\gamma_{m,\mathrm{air}}^0$；单位：1/cm，根据碰撞增宽可加性原理，将 $\gamma_{m,\mathrm{self}}^0$，$\gamma_{m,\mathrm{air}}^0$ 带入式(6) 中得到：

$$\gamma_m(P, T) = (T_0/T)^n (P/P_0)[\gamma_{m,\mathrm{self}}^0 (P_{\mathrm{self}}/P) + \gamma_{m,\mathrm{air}}^0 ((P - P_{\mathrm{self}})/P)] \tag{7}$$

式中：P_{self} 自增宽分压；n 温度指数。

3　计算结果和比较

以上推导的各个公式带入式(2) 中即可得到窄谱带模型参数 $\bar{k}$，$1/\bar{d}$ 和 γ。压力取为 0.1 MPa，温度区间 300～3 000 K，间隔 250 K。计算区间选择的是：50～10 000 cm^{-1}，间隔 10 cm^{-1}。由于篇幅关系，本文仅给出了研究高速飞行目标尾喷焰红外辐射问题及大气背景红外窗口辐射传输问题急需的水蒸气 2.7 μm 谱带模型参数，见表 1。

表 1　水蒸气 2.7 μm 谱带窄谱带模型参数

波数	300 K			500 K			750 K			1 000 K			1 250 K			1 500 K		
	$\bar{k}$	$1/\bar{d}$	γ	$\bar{k}$	$1/\bar{d}$	γ	$\bar{k}$	$1/\bar{d}$	γ	$\bar{k}$	$1/\bar{d}$	γ	$\bar{k}$	$1/\bar{d}$	γ	$\bar{k}$	$1/\bar{d}$	γ
3 300.	.004 5	.22	.254	.007 3	.53	.152	.017 0	2.43	.102	.043 3	5.47	.077	.085 0	8.62	.062	.132 3	11.58	.052
3 310.	.004 4	.26	.256	.010 9	.40	.153	.020 2	1.51	.102	.030 5	4.80	.077	.042 9	10.17	.062	.056 9	16.04	.052
3 320.	.003 7	.39	.258	.010 0	.78	.154	.027 8	2.37	.103	.069 5	4.73	.077	.127 7	7.60	.062	.186 4	10.71	.052
3 330.	.005 6	.17	.253	.018 9	.28	.151	.035 5	1.10	.101	.053 0	3.56	.076	.072 4	7.68	.061	.092 3	12.47	.052
3 340.	.001 2	.31	.257	.005 8	.76	.154	.026 6	2.11	.103	.075 1	4.10	.077	.137 1	6.67	.062	.194 6	9.58	.052
3 350.	.005 0	.25	.260	.015 1	.40	.156	.035 7	1.22	.104	.066 2	3.15	.078	.099 4	6.14	.063	.129 7	9.71	.053
3 360.	.011 6	.42	.258	.023 4	.57	.155	.042 7	1.74	.103	.074 8	4.22	.078	.113 5	7.50	.063	.149 5	11.04	.053
3 370.	.001 2	.31	.265	.008 5	.57	.159	.039 1	1.40	.106	.089 6	3.09	.080	.142 0	5.61	.064	.185 0	8.63	.054
3 380.	.005 6	.22	.258	.013 2	.58	.155	.036 6	1.70	.103	.072 2	3.88	.078	.107 6	7.12	.063	.136 2	10.98	.053

表 1　续

波数	300 K			500 K			750 K			1 000 K			1 250 K			1 500 K		
	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$
3 390.	.012 9	.22	.266	.033 6	.45	.159	.086 9	1.31	.106	.169 0	2.88	.080	.248 8	5.10	.064	.308 2	7.72	.054
3 400.	.003 4	.29	.261	.012 0	.46	.156	.029 7	1.56	.104	.049 4	4.47	.078	.068 7	9.08	.063	.086 4	14.36	.053
3 410.	.003 6	.27	.273	.022 8	.48	.164	.096 2	1.01	.109	.194 7	2.15	.082	.277 1	3.90	.066	.329 8	6.07	.056
3 420.	.015 4	19	.268	.037 4	.38	.161	.076 9	1.18	.107	.119 7	3.01	.081	.154 9	5.89	.065	.179 3	9.45	.055
3 430.	.004 8	.43	.263	.035 1	.54	.158	.137 5	1.03	.105	.251 4	2.14	.079	.331 6	3.84	.064	.372 8	5.97	.054
3 440.	.035 5	.29	.265	.066 3	.44	.158	.097 9	1.22	.106	.125 6	3.28	.080	.149 1	6.71	.064	.167 5	10.91	.054
3 450.	.002 8	.33	.267	.034 3	.32	.160	.118 6	.63	.107	.195 9	1.38	.080	.241 5	2.67	.065	.259 2	4.46	.054
3 460.	.015 6	.30	.272	.060 4	.36	.163	.148 7	.73	.109	.224 8	1.69	.082	.271 6	3.32	.066	.293 2	5.51	.055
3 470.	.008 1	.32	.263	.031 6	.45	.158	.076 1	.93	.105	.111 8	2.15	.079	.133 4	4.28	.064	.144 2	7.18	.054
3 480.	.035 7	.31	.272	.122 2	.35	.163	.272 5	.62	.109	.381 4	1.31	.082	.431 8	2.52	.066	.440 4	4.26	.055
3 490.	.016 1	.24	.271	.051 8	.34	.162	.099 5	.76	.108	.128 8	1.93	.081	.141 7	4.20	.066	.145 2	7.59	.055
3 500.	.067 7	.36	.269	.229 2	.38	.161	.434 5	.62	.107	.539 1	1.31	.081	.561 8	2.61	.065	.540 5	4.58	.055
3 510.	.015 9	.38	.266	.043 3	.49	.159	.076 7	1.10	.106	.099 1	2.83	.080	.112 5	6.10	.064	.120 8	10.71	.054
3 520.	.090 9	.35	.276	.271 1	.33	.165	.452 4	.55	.110	.524 4	1.18	.083	.526 2	2.39	.067	.495 2	4.23	.056
3 530.	.029 0	.26	.271	.094 4	.28	.163	.148 6	.63	.108	.169 5	1.75	.082	.174 0	4.11	.066	.172 7	7.65	.055
3 540.	.102 3	.33	.266	.312 9	.28	.159	.464 7	.51	.106	.500 1	1.23	.080	.479 5	2.73	.064	.439 9	5.17	.054
3 550.	.054 3	.33	.268	.098 3	.42	.160	.128 8	.95	.107	.139 9	2.54	.081	.143 5	5.69	.065	.145 6	10.18	.055
3 560.	.296 8	.39	.273	.637 0	.32	.164	.764 4	.46	.109	.721 9	.96	.082	.629 1	2.02	.066	.535 1	3.79	.056
3 570.	.041 6	.29	.275	.057 8	.36	.165	.075 5	.96	.110	.093 6	2.63	.083	.109 7	5.64	.067	.122 5	9.65	.056
3 580.	.310 6	.32	.273	.582 0	.29	.163	.631 8	.48	.109	.567 6	1.11	.082	.483 8	2.52	.066	.410 0	4.94	.056
3 590.	.150 8	.31	.267	.221 0	.34	.160	.237 5	.70	.107	.231 9	1.80	.080	.221 1	4.11	.065	.210 6	7.64	.054
3 600.	.321 6	.20	.269	.445 5	.20	.161	.422 3	.40	.108	.360 5	1.13	.081	.304 5	2.84	.065	.263 1	5.71	.055
3 610.	.509 3	.28	.268	.603 2	.24	.161	.528 6	.42	.107	.436 4	1.12	.081	.364 7	2.86	.065	.315 6	5.83	.055
3 620.	.646 3	.16	.264	.695 8	.15	.158	.570 2	.29	.106	.449 4	.85	.080	.361 3	2.24	.064	.302 1	4.67	.054
3 630.	.105 0	.17	.270	.102 8	.26	.162	.098 8	1.07	.108	.110 8	3.50	.081	.133 3	7.21	.065	.157 1	11.14	.055
3 640.	.611 7	.19	.259	.556 1	.19	.155	.419 6	.41	.104	.325 7	1.26	.078	.270 9	3.17	.063	.239 8	6.08	.053
3 650.	.497 7	.12	.272	.422 1	.16	.163	.332 5	.48	.109	.295 2	1.50	.082	.284 8	3.35	.066	.281 8	5.71	.055
3 660.	.164 2	.09	.265	.137 4	.19	.159	.136 1	.80	.106	.160 9	2.32	.080	.189 9	4.54	.064	.211 0	7.07	.054
3 670.	1.202 7	.18	.264	.835 4	.20	.158	.573 2	.48	.105	.452 5	1.32	.079	.391 3	2.85	.064	.352 1	4.88	.054
3 680.	.538 7	.08	.263	.353 0	.16	.157	.305 2	.54	.105	.322 7	1.34	.079	.339 0	2.53	.064	.338 5	4.02	.054
3 690.	.216 4	.28	.259	.181 5	.44	.155	.220 3	.79	.103	.264 5	1.45	.078	.283 0	2.52	.063	.278 7	3.96	.053
3 700.	.310 5	.24	.262	.250 3	.38	.157	.283 8	.62	.105	.312 1	1.11	.079	.312 3	1.95	.063	.293 1	3.14	.053
3 710.	.471 1	.21	.258	.469 6	.31	.154	.520 2	.48	.103	.516 6	.87	.077	.472 5	1.60	.062	.413 5	2.71	.053
3 720.	.294 6	.31	.264	.523 8	.31	.158	.624 1	.41	.105	.597 5	.70	.079	.522 3	1.27	.064	.438 9	2.20	.054
3 730.	.917 8	.31	.258	.929 0	.30	.154	.791 5	.39	.103	.633 2	.71	.077	.497 3	1.40	.062	.391 1	2.60	.053
3 740.	1.648 9	.32	.257	1.192 3	.29	.154	.804 1	.38	.102	.562 5	.71	.077	.405 2	1.49	.062	.300 9	2.94	.052
3 750.	.881 1	.22	.260	.589 8	.23	.156	.390 4	.40	.104	.276 0	.97	.078	.205 3	2.36	.063	.160 5	4.91	.053
3 760.	.311 9	.19	.250	.228 0	.25	.149	.168 4	.54	.100	.132 3	1.46	.075	.109 4	3.50	.061	.094 8	6.80	.051
3 770.	.135 5	.17	.244	.086 7	.30	.146	.069 7	.92	.098	.065 5	2.83	.074	.065 1	6.69	.059	.066 5	12.11	.050
3 780.	.052 5	.30	.253	.057 1	.49	.151	.066 1	1.22	.101	.071 5	3.20	.076	.074 7	6.82	.061	.076 9	11.64	.052
3 790.	.152 2	.13	.248	.100 0	.23	.149	.078 1	.81	.099	.070 1	2.84	.075	.068 1	7.03	.060	.069 6	12.64	.051
3 800.	.948 8	.13	.253	.485 5	.16	.151	.281 5	.43	.101	.195 1	1.44	.076	.152 3	3.77	.061	.129 8	7.48	.052
3 810.	.568 9	.10	.251	.321 5	.16	.150	.207 1	.51	.100	.160 1	1.70	.076	.137 6	4.26	.061	.125 9	8.10	.051
3 820.	.556 3	.18	.252	.326 7	.19	.151	.199 6	.40	.101	.139 5	1.26	.076	.108 7	3.42	.061	.093 2	7.06	.052
3 830.	.934 1	.14	.251	.578 0	.16	.151	.375 9	.33	.101	.276 9	.96	.076	.220 3	2.45	.061	.185 8	5.00	.052
3 840.	.272 3	.24	.250	.223 7	.29	.150	.172 7	.68	.100	.145 1	1.88	.075	.131 1	4.26	.061	.124 5	7.55	.051
3 850.	1.442 4	.21	.249	1.030 8	.20	.149	.689 7	.31	.100	.489 8	.73	.075	.365 0	1.71	.061	.284 3	3.51	.051
3 860.	.492 0	.18	.250	.441 2	.20	.150	.343 6	.39	.100	.276 6	.98	.075	.232 4	2.25	.061	.202 4	4.26	.051
3 870.	.516 1	.16	.244	.474 8	.18	.146	.377 3	.39	.098	.305 7	1.07	.074	.256 1	2.58	.059	.221 8	4.96	.050

表1 续

波数	300 K			500 K			750 K			1 000 K			1 250 K			1 500 K		
	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$
3 880.	.517 1	.23	.236	.582 2	.23	.141	.501 9	.37	.095	.412 8	.85	.071	.339 4	1.89	.058	.283 2	3.65	.049
3 890.	.439 9	.23	.232	.523 9	.23	.139	.466 4	.39	.093	.389 8	.90	.070	.325 1	2.03	.057	.276 2	3.87	.048
3 900.	.457 7	.21	.233	.636 5	.21	.140	.603 5	.35	.093	.513 8	.79	.070	.428 8	1.74	.057	.360 8	3.28	.048
3 910.	.114 8	.13	.231	.239 3	.16	.138	.286 1	.33	.092	.280 8	.83	.070	.259 1	1.86	.056	.234 7	3.45	.048
3 920.	.156 1	.28	.230	.264 5	.29	.138	.298 9	.49	.092	.294 0	1.03	.069	.275 4	2.06	.056	.252 5	3.58	.047
3 930.	.100 4	.19	.228	.267 7	.17	.136	.351 1	.31	.091	.350 2	.75	.069	.320 5	1.66	.056	.286 4	3.12	.047
3 940.	.125 2	.20	.227	.357 9	.20	.136	.488 8	.31	.091	.495 8	.62	.069	.453 3	1.25	.055	.398 7	2.25	.047
3 950.	.023 8	.32	.228	.061 3	.35	.137	.104 8	.63	.091	.134 3	1.41	.069	.151 2	2.82	.056	.159 2	4.78	.047
3 960.	.023 5	.19	.221	.119 9	.17	.133	.223 4	.31	.089	.268 4	.72	.067	.275 8	1.50	.054	.265 3	2.67	.046
3 970.	.019 7	.38	.213	.094 9	.32	.128	.200 4	.47	.085	.258 1	.90	.065	.273 3	1.68	.052	.265 3	2.80	.044
3 980.	.006 6	.27	.223	.036 2	.27	.133	.088 1	.51	.089	.125 0	1.14	.067	.143 9	2.25	.055	.150 9	3.79	.046
3 990.	.011 9	.24	.215	.064 6	.25	.129	.145 4	.46	.086	.198 7	.98	.065	.222 7	1.87	.053	.227 6	3.10	.045

表1 续

波数	1 750 K			2 000 K			2 250 K			2 500 K			2 750 K			3 000 K		
	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$
3 300.	.174 7	14.24	.045	.206 8	16.55	.040	.226 6	18.54	.036	.235 4	20.24	.033	.235 3	21.70	.031	.228 9	22.96	.029
3 310.	.070 8	21.18	.045	.082 8	25.24	.040	.091 7	28.31	.036	.097 1	30.62	.033	.099 2	32.35	.031	.098 7	33.69	.029
3 320.	.233 6	13.78	.045	.265 3	16.65	.040	.281 5	19.23	.037	.285 0	21.52	.034	.279 2	23.52	.031	.267 3	25.27	.029
3 330.	.109 9	17.03	.045	.123 4	20.95	.040	.131 8	24.17	.036	.135 4	26.76	.033	.135 0	28.85	.031	.131 5	30.54	.029
3 340.	.236 7	12.56	.045	.261 9	15.41	.040	.271 8	18.04	.037	.270 1	20.41	.034	.260 6	22.50	.031	.246 3	24.35	.029
3 350.	.153 3	13.34	.046	.169 1	16.69	.041	.177 3	19.62	.037	.179 0	22.11	.034	.175 6	24.21	.031	.168 8	25.97	.030
3 360	.176 3	14.46	.046	.192 7	17.59	.041	.199 2	20.33	.037	.198 0	22.70	.034	.191 4	24.72	.031	.181 5	26.44	.029
3 370.	.214 0	11.80	.047	.229 7	14.83	.041	.234 3	17.60	.038	.230 4	20.04	.034	.220 9	22.17	.032	.208 0	24.02	.030
3 380.	.155 4	14.97	.046	.166 0	18.74	.041	.169 2	22.08	.037	.166 7	24.97	.034	.160 4	27.40	.031	.151 7	29.44	.030
3 390.	.342 0	10.50	.047	.354 2	13.22	.042	.349 8	15.77	.038	.334 4	18.09	.035	.312 7	20.18	.032	.288 1	22.03	.030
3 400.	.100 8	19.37	.046	.111 2	23.62	.041	.117 0	27.05	.037	.118 8	29.74	.034	.117 3	31.84	.032	.113 4	33.48	.030
3 410.	.353 3	8.44	.048	.355 2	10.83	.043	.342 2	13.13	.039	.320 5	15.27	.035	.294 6	17.22	.033	.267 3	18.98	.031
3 420.	.192 6	13.20	.047	.196 9	16.77	.042	.194 3	19.96	.038	.186 7	22.72	.035	.176 1	25.07	.032	.163 8	27.03	.031
3 430.	.382 0	8.33	.047	.370 7	10.75	.041	.347 0	13.10	.037	.317 5	15.31	.034	.286 2	17.35	.032	.255 7	19.19	.030
3 440.	.179 1	15.19	.047	.184 3	19.11	.042	.183 6	22.50	.038	.178 2	25.34	.035	.169 6	27.68	.032	.159 1	29.60	.030
3 450.	.257 2	6.62	.047	.244 4	8.96	.042	.225 8	11.33	.038	.205 0	13.62	.035	.184 2	15.74	.032	.164 5	17.68	.030
3 460.	.296 2	8.02	.048	.287 3	10.63	.043	.271 1	13.14	.039	.251 0	15.45	.035	.229 5	17.53	.033	.208 0	19.37	.031
3 470.	.147 1	10.51	.047	.144 9	13.91	.041	.139 3	17.12	.037	.131 6	19.99	.034	.122 7	22.48	.032	.113 4	24.59	.030
3 480.	.423 0	6.39	.048	.392 8	8.74	.043	.357 1	11.15	.039	.320 5	13.50	.035	.285 5	15.72	.033	.253 3	17.75	.031
3 490.	.143 2	11.73	.048	.138 6	16.10	.042	.132 4	20.27	.038	.125 1	23.97	.035	.117 3	27.13	.033	.109 2	29.76	.031
3 500.	.498 1	7.11	.047	.449 4	10.01	.042	.400 7	13.04	.038	.355 2	16.02	.035	.314 1	18.82	.033	.277 7	21.38	.031
3 510.	.125 9	15.85	.047	.128 7	20.76	.042	.129 2	24.99	.038	.127 4	28.43	.035	.123 7	31.14	.032	.118 5	33.25	.030
3 520.	.450 2	6.60	.049	.402 9	9.31	.043	.357 2	12.15	.039	.315 3	14.95	.036	.278 1	17.58	.033	.245 3	19.98	.031
3 530.	.168 9	11.83	.048	.163 9	16.02	.043	.157 5	19.80	.039	.149 7	23.02	.035	.140 9	25.68	.033	.131 5	27.83	.031
3 540.	.395 8	8.39	.047	.354 3	12.07	.042	.316 6	15.88	.038	.282 9	19.52	.035	.253 0	22.84	.032	.226 4	25.77	.031
3 550.	.146 8	15.21	.047	.146 9	20.00	.042	.145 1	24.14	.038	.141 3	27.55	.035	.135 7	30.27	.033	.128 9	32.42	.031
3 560.	.452 4	6.22	.048	.384 4	9.12	.043	.328 8	12.21	.039	.283 3	15.28	.036	.245 8	18.17	.033	.214 5	20.78	.031
3 570.	.131 2	14.01	.049	.136 0	18.20	.043	.137 0	21.91	.039	.134 7	25.08	.036	.130 0	27.71	.033	.123 7	29.88	.031
3 580.	.350 1	8.28	.048	.303 2	12.19	.043	.265 8	16.25	.039	.235 2	20.11	.036	.209 4	23.58	.033	.187 2	26.60	.031
3 590.	.200 6	11.91	.047	.190 8	16.30	.042	.180 4	20.39	.038	.169 2	23.97	.035	.157 4	27.02	.033	.145 3	29.58	.031
3 600.	.233 0	9.43	.048	.210 4	13.44	.042	.191 8	17.25	.038	.175 5	20.63	.035	.160 4	23.51	.033	.146 3	25.92	.031
3 610.	.280 8	9.70	.047	.254 9	13.87	.042	.233 1	17.88	.038	.213 5	21.47	.035	.195 0	24.56	.033	.177 7	27.18	.031
3 620.	.260 8	7.89	.047	.230 7	11.44	.042	.206 6	14.92	.038	.185 8	18.09	.035	.167 3	20.86	.032	.150 4	23.26	.030
3 630.	.175 1	14.73	.048	.185 0	17.82	.042	.186 8	20.43	.038	.182 1	22.64	.035	.173 1	24.51	.033	.161 6	26.10	.031

表 1　续

波数	1 750 K			2 000 K			2 250 K			2 500 K			2 750 K			3 000 K		
	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$	$\bar{k}$	$1/\bar{d}$	$\bar{\gamma}$
3 640.	.219 3	9.46	.046	.202 9	12.83	.041	.187 4	15.90	.037	.171 9	18.59	.034	.156 5	20.91	.032	.141 5	22.89	.030
3 650.	.275 3	8.18	.048	.263 2	10.56	.043	.246 0	12.75	.039	.225 7	14.73	.036	.204 3	16.50	.033	.183 1	18.08	.031
3 660.	.219 7	9.64	.047	.217 8	12.10	.042	.207 9	14.39	.038	.193 3	16.46	.035	.176 5	18.32	.033	.159 3	19.98	.031
3 670.	.318 2	7.15	.047	.285 8	9.47	.042	.254 1	11.72	.038	.224 0	13.82	.035	.196 3	15.76	.032	.171 4	17.53	.031
3 680.	.321 7	5.69	.047	.295 3	7.45	.041	.264 5	9.21	.038	.233 1	10.93	.035	.203 5	12.56	.032	.176 7	14.10	.030
3 690.	.259 7	5.71	.046	.234 2	7.64	.041	.206 9	9.65	.037	.180 6	11.65	.034	.156 6	13.57	.032	.135 5	15.38	.030
3 700.	.263 6	4.65	.046	.231 4	6.39	.041	.200 2	8.26	.038	.171 9	10.17	.035	.147 1	12.06	.032	.125 9	13.87	.030
3 710.	.352 3	4.21	.046	.296 7	6.01	.041	.248 7	8.02	.037	.208 4	10.12	.034	.175 1	12.22	.032	.147 8	14.26	.030
3 720.	.361 5	3.50	.047	.296 2	5.12	.042	.242 7	6.99	.038	.199 7	9.01	.035	.165 4	11.08	.032	.138 0	13.12	.031
3 730.	.309 5	4.33	.046	.247 9	6.54	.041	.201 1	9.08	.037	.165 2	11.78	.034	.137 5	14.48	.032	.115 7	17.07	.030
3 740.	.229 5	5.15	.046	.180 3	8.03	.041	.145 3	11.34	.037	.119 8	14.78	.034	.100 7	18.12	.032	.085 9	21.18	.030
3 750.	.131 1	8.56	.046	.111 1	12.85	.041	.096 9	17.22	.037	.086 0	21.23	.034	.077 2	24.68	.032	.069 8	27.52	.030
3 760.	.084 7	10.97	.045	.077 3	15.40	.040	.071 1	19.58	.036	.065 6	23.26	.033	.060 5	26.34	.031	.055 7	28.85	.029
3 770.	.068 1	18.04	.044	.069 2	23.53	.039	.069 5	28.13	.035	.068 7	31.76	.033	.066 8	34.54	.031	.064 1	36.64	.029
3 780.	.078 0	16.77	.045	.078 0	21.53	.040	.076 7	25.60	.037	.074 1	28.90	.034	.070 7	31.51	.032	.066 6	33.56	.030
3 790.	.071 9	18.34	.044	.073 8	23.31	.040	.074 4	27.29	.036	.073 4	30.38	.033	.071 2	32.74	.031	.067 9	34.53	.029
3 800.	.116 5	11.91	.045	.107 5	16.34	.040	.100 2	20.29	.037	.093 4	23.59	.034	.086 8	26.26	.032	.080 3	28.37	.030
3 810.	.118 5	12.54	.045	.112 9	16.89	.040	.107 4	20.74	.036	.101 5	23.96	.034	.095 2	26.56	.031	.088 7	28.63	.030
3 820.	.085 1	11.48	.045	.080 7	15.83	.040	.077 6	19.57	.037	.074 6	22.56	.034	.071 2	24.88	.032	.067 5	26.65	.030
3 830.	.162 7	8.33	.045	.146 2	11.94	.040	.133 1	15.41	.036	.121 8	18.49	.034	.111 6	21.10	.031	.102 1	23.26	.030
3 840.	.120 6	11.12	.045	.117 4	14.46	.040	.113 3	17.33	.036	.108 2	19.70	.034	.102 2	21.61	.031	.095 6	23.13	.030
3 850.	.229 4	6.10	.045	.191 2	9.21	.040	.163 1	12.51	.036	.141 6	15.69	.033	.124 4	18.57	.031	.110 2	21.07	.030
3 860.	.180 3	6.82	.045	.162 8	9.60	.040	.148 0	12.30	.039	.134 8	14.77	.034	.122 7	16.92	.031	.111 6	18.76	.030
3 870.	.196 2	7.96	.044	.176 2	11.17	.039	.159 2	14.26	.036	.144 2	17.05	.033	.130 6	19.47	.031	.118 2	21.52	.029
3 880.	.239 9	6.05	.042	.206 5	8.84	.038	.180 0	11.73	.035	.158 3	14.50	.032	.140 2	17.00	.030	.124 7	19.20	.029
3 890.	.238 7	6.28	.042	.209 7	8.97	.037	.186 0	11.66	.034	.166 1	14.15	.032	.148 7	16.37	.030	.133 4	18.28	.028
3 990.	.306 9	5.32	.042	.264 5	7.63	.038	.230 0	10.01	.034	.201 4	12.29	.032	.177 1	14.38	.030	.156 3	16.23	.028
3 910.	.211 1	5.47	.042	.189 7	7.71	.037	.170 5	9.94	.034	.153 0	12.04	.032	.137 3	13.94	.030	.123 1	15.60	.028
3 920.	.228 3	5.48	.041	.205 1	7.58	.037	.183 4	9.72	.034	.163 7	11.75	.031	.145 8	13.62	.030	.129 9	15.29	.028
3 930.	.254 4	5.01	.041	.226 5	7.13	.037	.201 9	9.26	.034	.180 3	11.27	.031	.161 0	13.09	.029	.143 9	14.70	.028
3 940.	.344 8	3.60	.041	.297 2	5.18	.037	.256 4	6.89	.034	.221 6	8.60	.031	.192 3	10.25	.029	.167 5	11.78	.028
3 950.	.160 3	7.05	.041	.157 0	9.40	.037	.150 5	11.63	.034	.141 9	13.65	.031	.132 3	15.43	.029	.122 2	16.98	.028
3 960.	.246 5	4.14	.040	.225 1	5.77	.036	.203 4	7.45	.033	.182 5	9.06	.031	.163 1	10.57	.029	.145 5	11.94	.027
3 970.	.245 8	4.20	.039	.222 4	5.75	.035	.198 6	7.36	.032	.175 9	8.93	.030	.155 3	10.41	.028	.136 9	11.77	.027
3 980.	.150 1	5.58	.040	.144 8	7.44	.036	.136 9	9.23	.033	.127 5	10.88	.031	.117 5	12.35	.029	.107 5	13.64	.028
3 990.	.220 6	4.57	.039	.207 6	6.15	.035	.191 5	7.73	.032	.174 4	9.24	.030	.157 5	10.64	.028	.141 5	11.91	.027

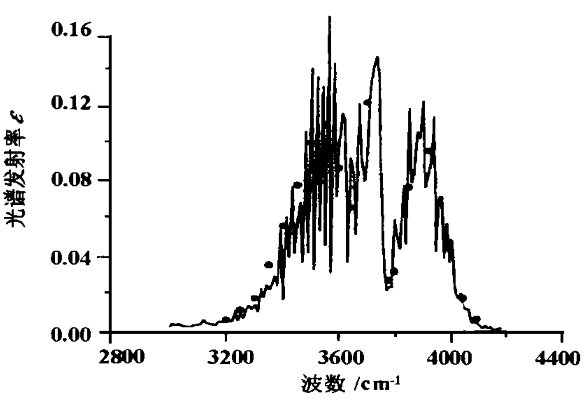

图 1　2.7 μ 带发射率计算值(—) 与实验值[5] (∘) 比较

P_{tot} = 0.1 MPa, X_{H_2O} = 0.358 9, T = 1 000 K, L = 3.12 cm

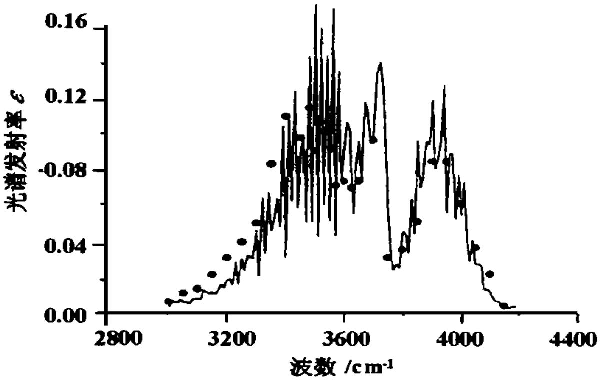

图 2　2.7 μ 带发射率计算值(—) 与实验值[5] (∘) 比较

P_{tot} = 0.1 MPa, X_{H_2O} = 0.525 6, T = 1 500 K, L = 3.12 cm

由表1的模型参数计算了不同条件下2.7μm谱带的光谱发射率和光谱平均吸收系数并与实验数据

和 NASA 数据进行了比较，如图 1 至图 4 所示，计算中考虑了碰撞增宽和多普勒增宽的影响。结果表明，计算光谱与实验光谱符合很好，仅在几个局部峰值与实验数据有较大偏差，而这可能是由于计算数据分辨率和实验数据分辨率不同造成的。总的看，本文得到参数是准确、可靠的。

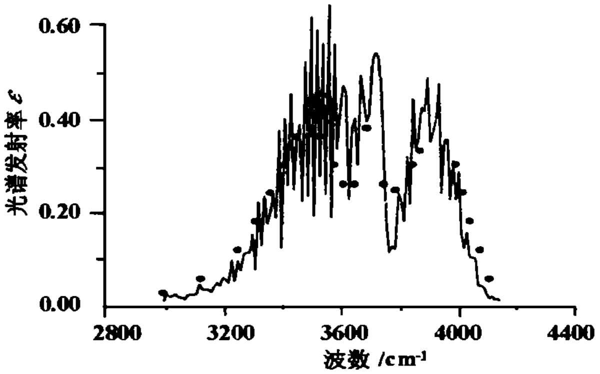

图3　2.7 μ 带发射率计算值(—)与实验值[6] (∘)比较

$P_{tot} = 0.0921$ MPa，$X_{H_2O} = 0.621$，$T = 1\,273$ K，$L = 12.72$ cm

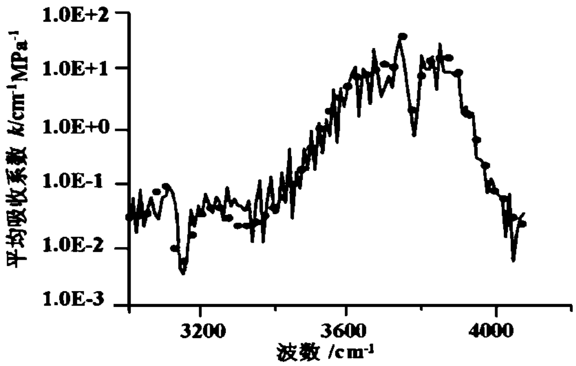

图 4　2.7 μ 吸收系数计算值(—)与 NASA 数据[7] (∘)比较

$P_{tot} = 0.1$ MPa，$T = 300$ K

4　结论

本文以最新的 HITEMP 数据库为基础计算得到了水蒸气 50 ~ 10 000 cm^{-1} 光谱区间的谱带模型参数 k，$1/\bar{d}$ 和 γ 数据表。通过与实验值比较表明本文所建立的数据表是可靠的，比 NASA 提供的数据表有了较大改进，使用起来也十分方便。特别是 6.3 μm，2.7 μm 谱带的参数表对飞行器尾喷焰的红外目标特性计算很急需。由于篇幅所限，本文仅给出了 2.7 μm 谱带的模型参数表，供工程计算引用，其它的模型参数收录在我们建立的尾喷焰气体分子红外辐射特性模型参数库中。

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（何静芳　编辑）

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(3) 混合物质在热重分析中的燃烧特性可以用单组分的物质燃烧特性的叠加来表示。某些混合试样的组分之间会表现出有相互影响，但一般说来并不强烈。

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（复　编辑）

direct-flow slit type burner. The 360 MW boiler is a product of French Stein Co. With the help of a hot-wire anemometer the velocity distribution of a flow field in the furnace was measured and the flow field diagram of W-shaped air flow in the furnace under various operating conditions obtained. An analysis has been perfomed with respect to the following: the law of air flow velocity distribution of the flow field under different operating regimes, the filling fullness of air within the furnace, the air flow path, velocity excursions at the furnace outlet, etc. Also studied are the in-furnace aerodynamic field characteristics and their variation law and mechanism along with a measurement of flame short circuiting of the W-shaped flame boiler and the velocity excursions at the furnace outlet. **Key words**: W-shaped flame, boiler, flame short circuiting, velocity excursion, cold-state model test, aerodynamic field

水平管道细粉高浓度分层流动阻力特性的试验研究＝**Experimental Research of the Resistance Characteristics of High-concentration Fine Powder Stratified Flow in a Horizontal Pipe** [刊, 汉] / Qiu Peng-hua, Chen Li-zhe, Wang Hong, *et al* (Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—23～25, 72

With a progressively better understanding of the advantages of a high-concentration fine powder conveying system the latter has recently become an object under extensive study by numerous scholars. A stratified flow in a horizontal pipe represents the most important form of high-concentration powder transport flow. In view of this the study of its resistance characteristics is of great significance. On the basis of a review of their work in this area over the past fifty years the authors have analyzed the merits and demerits of empiric formulas presented by various scholars. Through a series of tests on a test rig of high-concentration pneumatic conveying system, deduced is a formula for calculating the resistance characteristics of a high-concentration fine powder stratified flow in a horizontal pipe. An error analysis indicates that the above-mentioned formula can well meet the relevant requirements of general engineering design. **Key words**: pneumatic transport, hydrodynamic characteristics, resistance characteristics, gas-solid two-phase flow

论燃气轮机在天然气输气管道上的选用和配套＝**The Selection of Gas Turbines for Use in a Natural Gas Transmission Pipeline and the Supply of Necessary Supporting Auxiliaries** [刊, 汉] / Chen Reng-gui (Tarimo Petroleum Exploration and Development Command Headquarters, Kurle City, Xingjiang Autonomous Region, China, Post Code: 841000) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—26～29

A brief analysis was conducted of the major features of natural gas transmission piplines, natural gas compressors and gas turbines. On this basis some problems are highlighted, which merit special attention in the course of the selection of gas turbines for use in natural gas transmission pipelines and the appropriate provision of necessary supporting auxiliaries. **Key words**: natural gas transmission, compressor, gas turbine

新模式热电联产供热系统用热终端高效换热器的分析＝**The Analysis of a High-efficiency Heat Exchanger at the Heat User End for a New Mode of Cogeneration Heat Supply System** [刊, 汉] / Qiu Lin (Beijing Institute of Civil Engineering and Architecture, Beijing, China, Post Code: 100044) //Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—30～32

The present paper has proposed for a new mode of cogeneration low-grade heat supply system a high-efficiency heat exchanger at heat user' s end, which is composed of a new type of fan coil tubes. A discussion and analysis was conducted from the perspective of technical feasibility, energy-saving potential and cost-effectiveness. The aim of the above is to provide a theoretical basis for the implementation of a new mode of cogeneration heat supply system. **Key words**: co-production of heat and electrical power, low-grade heat supply, exergy efficiency

300～3 000 K 水蒸气红外辐射谱带模型参数＝**Infrared Radiative Spectral Band-model Parameters for Water Vapor in the** 300 - 3000 **K Temperature Range** [刊, 汉] / Dong Shi-kui, Tan He-ping, Yu Qi-zhang, Liu Lin-hua

(Energy Source College under the Harbin Institute of Technology, Harbin, China, Post Code: 150001)//Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—33～38

Spectral data of water vapor molecules have been widely used in the fields of aerospace science, atmospheric science, astrophysics, thermal energy and power engineering. On the basis of the newest high-resolution high-temperature gas spectral data base HITEMP and by way of a rational extrapolation obtained were the water vapor spectral band-model parameters in the 300 - 3000 K temperature range. The latter include an average absorption factor, spectral line density, spectral line half-width. As a result, set up was a more up-to-date and detailed model parameter table than that promulgated by NASA in 1973. With the model parameter table serving as a basis the authors have through the use of a statistical spectral band model calculated emission spectra under various optical paths, which have been found to be in very good agreement with experimental values. **Key words**: infrared radiation, water vapor, spectral band model parameter

N300 MW 机组振动爬升与低频振动的原因及其对策＝**An Analysis of the Causes of Climbing Vibrations and Low-frequency Ones in a N300 MW Unit and Some Measures Taken for Their Elimination** [刊, 汉] / Li Lu-ping, Zhou Ke (Changsha University of Electric Power Engineering, Changsha, China, Post Code: 410077), Zhang Guo-zhong, Huang Pi-wei (Hunan Provincial Electric Power Research Institute, Changsha, China, Post Code: 410070), Hu You-ping, Gan Fu-quan (Xiangtan Electric Power Co. Ltd., Xiangtan, Hunan, China, Post Code: 411100)//Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—39～42

On the basis of numerous test data obtained on-site the authors expounds the characteristic features of climbing and low-frequency vibrations in a Chinese-made 300 MW turbogenerator set and the causes of their emergence. Some technical measures have been recommended for their elimination. The on-site test results obtained after the implementation of these technical measures indicate that the measures adopted have been very effective in eliminating the above-mentioned vibrations. **Key words**: turbogenerator set, vibration, fault diagnosis

运行参数对粉煤流化床(PC—FB)燃烧效率的影响＝**The Effect of Operation Parameters on the Combustion Efficiency of a Pulverized-coal Fluidized Bed** [刊, 汉] / Chen Hong-wei (North China National Electric Power University, Baoding, Hebei, China, Post Code: 071003), Jin Bao-sheng, Xu Yi-qian (Southeastern University, Nanjing, China, Post Code: 210096)//Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—42～45

With the help of a pulverized-coal fluidized bed (PC-FB) test rig with 0.3 MW heat input test data were obtained of the PC-FB combustion efficiency under various operation parameters. A detailed discussion and study was conducted focusing on the mechanism of influence of these operation parameters on PC-FB combustion efficiency. The study results indicate that the combustion efficiency of the PC-FB can be as high as 98% - 99%, comparable with that of a pulverized-coal furnace. The authors also pointed out for the first time in the present study that under a certain set of conditions it is possible to realize a low-temperature high-efficiency combustion of the pulverized-coal. These conditions include, among others, a rational matching of the following items: combustion temperature, particle residence time, flame turbulence and in-furnace oxygen concentration and particle concentration. **Key words**: fluidized bed, pulverized coal, combustion efficiency, operating parameters

四角切向燃烧锅炉炉内气流流动特性及炉膛高度的选取＝**In-furnace Flue-gas Flow Characteristics and Selection of Furnace Height for a Tangentially Fired Boiler** [刊, 汉] / Zhou Yue-gui, Zhang Ming-chuan (Energy Source Department, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030, Ai Wei-guo, Xu Tong-mo, Hui Shien (Energy Source Department, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)//Journal of Engineering for Thermal Energy & Power. —2001, 16(1).—46～48, 42

With a model HG-2008/18.2-YM2 tangentially fired boiler serving as a prototype a cold-state modeling test was conducted with a view to studying the gas flow characteristics in the boiler furnace and the effect of furnace height on the gas ve-