循环流化床燃烧炉膛压降与轴向固体浓度

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[摘要]根据不同容量的循环流化床燃烧锅炉的实测数据，以及以前的研究结果，提出了压降沿炉膛高度分布的计算式，由此可计算固体浓度沿床高的分布，为炉膛设计提供了直接的依据。

关键词　循环流化床锅炉　压降分布　轴向固体浓度
分类号　TK223

1 前言

循环流化床锅炉燃烧条件下对炉膛内气固流动的研究，已有一些报导，内容包括沿炉膛高度的压降分布，轴向和径向固体浓度分布，固体流率分布及其对传热系数的影响。对循环床锅炉燃烧中气固流动的实际测量，目前可得到的资料有文献[1—8]。

对工程设计来说，需要使用可靠的公式，在给定参数的情况下，进行燃烧，传热的计算；然而，实验研究是在热态下对锅炉进行实测，再对所得数据处理、分析，然后再对实际运行的锅炉进行验证，所公布的结果还不能直接应用于工程设计计算。而在锅炉设计时，不可能对构思方案进行实测。因此，炉膛的设计需要一套设计计算公式，来计算确定具体的几何形状尺寸。其中，沿床高的压降分布具有十分重要的作用。本文根据研究者们对运行中锅炉的实测数据，结合以前提出的计算式[9]，提出了适用于循环床锅炉炉膛设计的压降分布计算式，以及据此计算的轴向固体浓度分布式，并使用实测数据进行了验证。

2 压降分布与轴向固体浓度分布关系

截面平均固体浓度 C_b 沿高度的分布与压降沿高度的分布，一定条件下存在下列关系：

$$-dp/dh = c_v \rho_s g = c_b g \qquad (1)$$

此式的使用基于以下假设：(1) 忽略气体、固体颗粒加速能量损失；(2) 忽略气体、固体、壁面之间的摩擦损失；(3) 气体密度 ρ_g 远小于固体密度 ρ_s。许多研究者采用此式，测量压降分布来确定截面平均固体浓度 c_b[4-6,8,11,12]。有的用直接测量的浓度数据与此法比较，认为符合良好[2,7]。P. Basu[10] 曾对此方法提出疑问，认为由壁面上静压测量得到的固体悬浮浓度可能低于实际浓度。因为向下流动的颗粒没有整个地由上升气流托起，相应的能量消耗小于上升颗粒。但 P. Basu 也曾在循环床锅炉燃烧研究中使用该方法[11]。在冷态循环流化床测量中测量压降来确定轴向固体浓度分布的研究报导更多。其

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中 Louge M. 等[12] 讨论了这种方法，结果指出，当固体循环率 G_s 和空隙率 ε 轴向梯度不大时，忽略加速、摩擦的影响，C_b 便可直接由压力梯度计算。

于是，设计炉膛计算传热系数所需的固体浓度，可依如下顺序计算：① 按照选定的 G_s、u_a 以及颗粒性质 d_p、ρ_s 等计算压力沿床高的分布；② 用式(1) 计算压力梯度和固体浓度分布 C_b；③ 用类似 W. Zhang 等[1,5] 的关联式计算局部固体浓度，进而计算局部传热系数。

3　压力分布计算式

本文使用文献[9]中的指数形式来表示炉膛内过渡区以上压力沿高度的分布，理由如下：① 冷态数据已经证明，指数式能很好地描述快速床的压力分布；② 循环床锅炉大部分床高为快速床，受热面将布置在该区域；浓相区和过渡区很短，且覆盖耐火材料，不布置受热面；③ 进一步将使用压力梯度计算轴向固体浓度，其中忽略加速影响，加速段应当在浓相区和过渡区(飞溅区)。本文着重于如何表达二次风口以上或给料口以上床高的压力分布。

用指数形式表示冷态循环床轴向空隙率的还有郭慕孙等[13]、国井等[14]。

由文献[9]，用无因次数群表示的压力沿床高的分布如下：

$$P/(\rho_a u_a^2) = C \cdot l/D \cdot m/F_r \cdot \rho_s/\rho_a \times (u_t/u_a)^{0.2} e^{-kh/H} \quad (2)$$

式中 $l = 1^m$，写作有因次形式

$$P = C\rho_s g m (u_t/u_a)^{0.2} e^{-kh/H} \quad (\text{Pa}) \quad (3)$$

式中 C、k 为常数，此时 C 具有了长度量纲。

轴向固体浓度分布，由式(1)、(3)，得

$$C_b = Ck/H \cdot \rho_s m (u_t/u_a)^{0.2} e^{-kh/H} \quad (\text{kg/m}^3) \quad (4)$$

4　与锅炉实测数据比较

4.1　与文献[2]的数据比较

加拿大 Chatham 的 72 MW 循环床锅炉，布风板到烟窗中心线高为 22.5 m；床料(70～80)% 为石灰与石灰石，1% 为煤炭，其余为煤灰。颗粒直径 $d_p = 250$ μm，$\rho_s = 2500$ kg/m³，$u_t = 1.618$ m/s；床温 850℃；$u_a = 6.4$ m/s；$G_s = 36.32$ kg/(m²·s)。对 $h \geqslant 3$ m 区域，压力分布表示为

$$P = 0.01043\rho_s g m (u_t/u_a)^{0.2} e^{-2.179h/H} \quad (5)$$

即

$$P = 3509e^{-2.179h/H} \quad (6)$$

与所测数据比较如图 1，平均误差 11.4%。

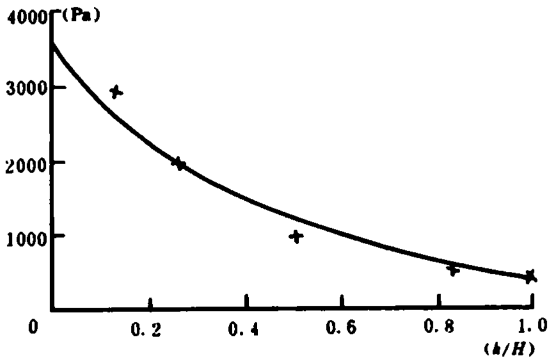

图 1　与文献[2]数据比较

4.2　与文献[3,4]的数据比较

B. Leckner 等的数据取自瑞典 Chalmers 大学的 12 MW 循环床锅炉。布风板到烟窗中心线 11 m；测量工况为 $u_a = 6$ m/s，颗粒 $d_p = 260$ μm，$\rho_s = 2600$ kg/m³，$u_t = 1.74$ m/s。

对 $h \geqslant 0.8$ m 区域，沿床高的压力分布为

$$P = 2281e^{-1.475h/H} \quad (7)$$

比较结果如图 2 中 a 所示，平均误差 5.8%。

再用文献[4]的一组数据，仍在这台锅炉测得：$u_a = 3.4$ m/s，$d_p = 320$ μm，$u_t = 2.2$ m/s。在 $h > 1$ m 区域，压力分布为

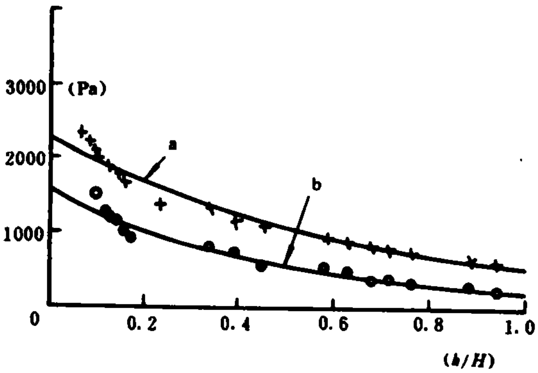

图 2　与文献[3、4]数据比较

$$P = 1534e^{1.963h/H} \tag{8}$$

如图 2 中 b 所示，平均误差 7.8%。

4.3　与文献[6]的数据比较

D. Westphalen 等用 2.5 MW 的循环床锅炉和冷态模拟实验台进行了比较，目的是为锅炉设计放大提供实验依据。该锅炉布风板到烟窗中心线高 7.3 m。颗粒 $d_p = 240\ \mu m$，$\rho_s = 2600\ kg/m^3$。为了便于和文献[2,3]比较，取运行工况相近一组数据 $u_a = 7.6\ m/s$，$G_s = 32\ kg/(m^2 \cdot s)$。

文献[6]给出的是 C_v 沿床高的分布，没有压力数据。把该组数据转换为 C_b，再根据式(4)，得 $C = 0.01074$，$k = 1.905$ 于是有

$$C_b = 71.47e^{-1.905h/H} \tag{9}$$

比较如图 3 所示，平均误差 11.4%。

由此可推定压力分布应为

$$P = 2684e^{-1.905h/H} \tag{10}$$

如图 4 所示。

4.4　与文献[8]的关联式比较

R. Divilio 等从几台大型循环床锅炉上取得数据(没公布数据)，表明在二次风口以上，固体浓度沿床高的分布符合

$$C_b = bh^a$$

但宣称，根据几台大型锅炉的数据，常数 $a = -1.12$；b 由某两个高度之间的压降来计算。他们用式(1)与上式相等，从 h_1 到 h_2 积分，得

$$C_b = \frac{(a+1)P_{1-2}}{h_2^{a+1} - h_1^{a+1}}h^a \tag{11}$$

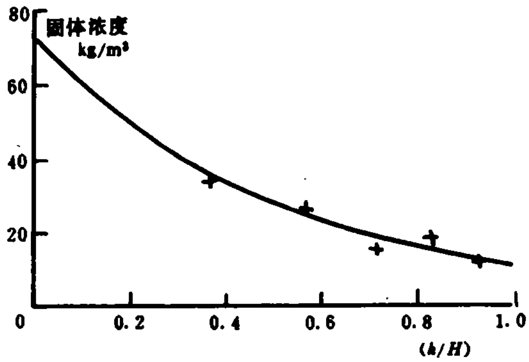

图 3　与文献[6]数据比较

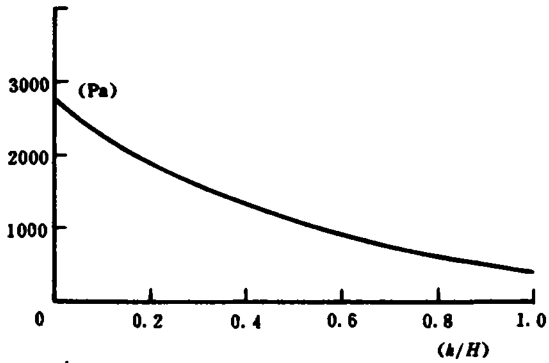

图 4　由式(9)推得压力分布

式中 P_{1-2} 即 h_1 到 h_2 的压降，Pa。该文以一台高 30 m 的炉子为例，取 $h_1 = 4$ m，$h_2 = 24$ m，$P_{1-2} = 2491.7$ Pa，得

$$C_b = 1825\ h^{-1.12} \tag{12}$$

这里，由式(3)，当 $h = 0$

则　　$P_0 = c\rho_s g m(u_t/u_a)^{0.2}$

即有　　$P = P_0 e^{-kh/H}$　　(13)

于是式(4)可写作

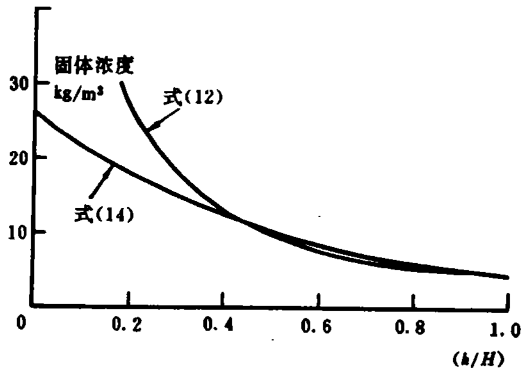

图 5 式(14)与式(12)比较

$$C_b = P_0k/(Hg)e^{-kh/H}$$

从文献[8]知，该锅炉布风板到烟窗中心线高 27 m；又 $P_0 = 2541$ Pa，取 $k = 1.773$，有

$$C_b = 25.73e^{-1.773h/H} \quad (14)$$

将式(14)与式(12)比较，如图 5 所示。当 $H > 9$ m，两曲线几乎重合，误差小于 10%，这说明，式(4)能在过渡区以上准确地表达式(11)所表示的固体浓度分布。反之，式(11)却不能用于其它文献(如[3,4,6])的数据。原因是式(11)中积分得到的

$$b = (a+1)P_{1-2}/(h_2^{a+1} - h_1^{a+1})$$

并不总是等于 dp/dh，导数 dp/dh 是沿高度变化的，因此 b 值不能任意取两点来确定。

另外，文献[2]和 B. Leckner 等的一些运行工况相近的轴向固体浓度数据，与式(4)计算值比较，结果基本符合。

5 常数 C、k 之值

由上述结果可见，在通常循环床锅炉操作范围内，C 值变化不大。2.5 MW 和 72 MW 两台炉子中，G_s、u_a 相差不多，C 值也非常接近。k 值在本文所举的运行工况下，为 1.475～2.179，其变化范围大于 C 值的变化。k 在国井等的式子中称为衰减常数。国井等[14]指出，dp 相同的颗粒，ku_a = 常数，并有冷态数据为证。本文的热态数据不符合这一规律。但定性说来，u_a 小则 k 大，即 u_a 小时，P、C_b 沿床高衰减加快。

6 结论

选定 u_a、G_s 和颗粒等主要参数，可使用式(3)、(4)来计算炉膛内快速床区域沿高度的压力及轴向固体浓度公布。

本文列举的锅炉运行工况下，式(3)、(4)中 C 值为 0.01043～0.01074；k 值为 1.475～2.179

循环床锅炉中影响轴向固体浓度分布的主要参数是空截面气速 u_a 和固体循环流率 G_s；以及颗粒性质。

符号说明

C_b— 截面平均固体浓度，kg/m³
C_v— 平均固体容积份额
d_p— 颗粒平均直径，μm
D— 床径，m
G_s— 固体循环流率，kg/(m²·s)
Fr— 付汝德数，u_a^2/gD
h、H— 距布风板高度和床总高，m
l— 定性尺度，m
m— 气固比，$G_s/\rho_a u_a$
P— 压力，Pa
P_{1-2}—h_1 到 h_2 的压降，Pa
u_a— 空截面气体速度，m/s
u_t— 颗粒终端沉降速度，m/s
ρ_a— 气体密度，kg/m³
ρ_s— 颗粒密度，kg/m³

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未来的潜艇发动机

据“U. S. Naval Institute Proceedings”1994 年 6 月号报道，现在已证实了燃气轮机在船舶应用中的效用，积累了数百万可靠的运行小时。气冷反应堆已可以高达 950℃的冷却剂温度运行并具有杰出的可靠性和十分低的冷却剂放射性水准。

在气冷反应堆—燃气轮机闭式循环系统中，压气机提高氦气的压力。对于感兴趣的温度，最佳压比约为 5：1 或 6：1。已增压的氦气流过石墨减速反应堆被加热。高温并经过压缩的氦气通过涡轮膨胀产生机械功。然后，经过膨胀的氦气被冷却，使其熵值回到起始点，并重新开始此过程。此系统是闭式的，只输出功和排出废热。

压气机通常是离心式的。为了得到对应于最大效率所需要的压比(4：1 到 7：1)，该离心式压气机可以包含几级。压气机可以直接由涡轮驱动或由涡轮带动的发电机输出的电力驱动。动力涡轮可以是轴流式的。

不像压水堆—汽轮机装置受温度限制那样，气冷堆—闭式循环燃气轮机装置可以设计成取得材料技术进展方面的优点，该进展可允许进一步提高堆芯的温度。例如，如果允许把系统的最大温度从 950℃增加到 1050℃，则将使输出的比功几乎增加 20%，最大效率可从约 35%增加到 38%。

气冷堆—闭式循环燃气轮机装置具有下列优点：

1. 费用节省。核等级材料和制造费用是十分昂贵的。此系统能减少材料、焊接和部件的数量，从而减少了费用。

2. 减少了制造的工作量。管道—系统的制造是困难和费时的，尤其是在空间受限制的船舶和潜艇中。此系统减少了管道系统，从而也减少了装备时间。

3. 增加了热力学效率。这是高循环温度的直接结果。即使采用保守的假设，此系统很容易达到 30%热效率；与之相比较，压水堆—汽轮机装置的效率约为 20%。

4. 减少了需要的人力。较少的部件意味着较少的监视站和较少的值班记录。

5. 减少了辐射量。压水堆装置中最大的辐射量是腐蚀性产物影响的结果。气冷堆—闭式循环燃气轮机装置消除了腐蚀源(高温的水)，从而减少了此问题。

6. 增加了比功(功率与重量之比)。压水堆—汽轮机装置的一些部件，如蒸汽发生器、增压装置、充水储罐、储备供给罐、均压罐和高压隔声管道系统是很重的。此外，气冷堆—闭式循环燃气轮机装置还减少了二次屏蔽。这一切均显著增加了比功并减少了装置占地空间。

研究表明，高温气冷堆—闭式循环燃气轮机装置很可能是二十一世纪核潜艇的主动力装置。(学牛供稿)

向心汽轮机与热电冷三联产——热电联产工程系列报告之三＝Centripetal Turbines and Simultaneous Production of Heat Energy, Electricity and Refrigeration-the Third in a Series of Reports Concerning the Cogeneration of Heat and Electricity[刊,中]/Yu Hongqing, Ye Zhaogu, Qiang Guofang(Harbin Marine Boiler & Turbine Research Institute)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -129-134

The authors give a description of the performance, construction and certain technical details of a recently developed radial-flow centripetal back-pressure turbine with a Curtis stage, followed by an exploratory study of some typical engineering applications of such turbines in the cogeneration of heat and electricity (including refrigeration). Key words: centripetal steam turbine, Curtis stage, simultaneous production of heat energy, electricity and refrigeration

射水抽气器改进的方法＝A Method for the Imprvment of Water-jet Air Ejectors[刊,中]/Xiao Hancai(Changsha Electrical Power Institute)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -135-139

The stuctural desgin of certain low-efficiency water-jet air ejectors os analysed with its irrationality being pinpointed. On this basis an improved method is proposed. The author explained why a long throat tube and mulitple nozzles should be utilized in preference to a short throat tube and single nozzle in order to enhance air extraction efficiency. In conclusion, by citing some specific examples presented in this paper are the design method, procedures for its improvement and comparison of results before and after the introduction of the improved design. Key words: air ejector, nozzle, throt tube, efficiency

百叶窗煤粉浓缩器气流和静压分配问题＝On the Flow Rate and Static Pressure Distribution of a Louvered Pulverized Coal Concentrator [刊,中]/Xing Chunli, Qin Yukun(Harbin Institute of Technology)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -140-143

The exit area ratio amd blade coverage ratio of a louvered pulverized coal concentrator which exercise a major influence on its performance are studied by the authors as to their effect on the flow rate and static pressure distibution of the said concentrator. The study results show that for a given structural design of the louver there exists an exit area ratio which can ensure a uniform distribution of the flow rate and static pressure between two exits of the louvered pulverized coal concentrator. Key words: louver, concentrator, distribution

矩形平壁循环流化床冷态流动特性研究＝A Study on the Cold-state Flow Characteristics of a Rectangular Flat Wall Circulating Fluidized Bed[刊,中]/Huang Suhua, Lu Jidong, Qian Shizhi, et al (Central China University of Science and Technology)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -144-148

With air serving as fluidized medium and samd(0.1-0.45mm)as bed material the concentraion distribution of axial and radial particles has been separately determined on a circulating fluidized bed cold-state test rig through the use of a reflexive optical fiber probe. A special study is conducted of the effect of the rectangular section circulating bed edge angle on the gas-solid dual-phase flow and the radial particle concentration distribution. Also studied is the gas-solid flow in the neighborhood of the wall surface. An sequential analysis method hsa been introduced to establish a parameter model for the sampled data. The experimental re-sults can play a significant role in achieving an in-depth understanding of the gas-solid dual-phase flow in the circulating fluidized bed. Key words: circulating fluidized bed, rectangular section, particle concentration, AR model

循环流化床燃烧炉膛压降与轴向固体浓度＝The Combustion Furnace Pressure Drop of a Circulating Fluidized Bed and Axial Solid Concentration[刊,中]/Li Yintang, Li Jun, Che Defu(Xi'an Jiaotong University)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -149-153

Based on the measred data of a citculating fluidized bed combustion boiler of various capacity and previous study results. the authors propose an equation for calculating the distribution of pressure drop along the furnace height, thus making it possible to calculate the distribution of solid concentration along the bed height, which can serve as a direct basis for the furnace design. Key words: circulating fluidized bed boller, pressure drop distribution, axial solid concentration

煤热解的反应动力学研究＝A Study on Coal Pyrolysis Reaction Dynamics[刊，中]/Xu Yuenian (Southeastern University)//Journal of Engineering for Thermal Energy & Power. -1995,10(3). -154-157

A great deal of experimental research work on coal pyrolysis was performed by using a TGA92 thermoanalyser of French make. The factors affecting coal pyrolysis were discussed. On the basis of the thermal analysis results the equation of coal pyrolysis dynamics and its relevant parameters were determined. finally, an in-depth exploratory study was conducted of the pyrolysis reaction rate, a key factor for the pyrolysis furnace productivity. Key words: thermogracimetry, derivative thermogravimetry, differential thermal analysis

CFBC 锅炉内多重内循环燃烧技术研究与应用＝The Research and Application of Multiple In-furnace Circulating Combustion Technology for a CFBC Boller[刊，中]/Jiang Xiumin, et al (Northeastern Institute of Electric Power Engineering)//Journal of Engineering for Thermal Energy & Power. -1995,10(3). -158-161,185

The principle and structure of multiple in-furnace cerculating combustion technology of a CFBC boiler comprising inner circulating combustion technoloby of furnace lower portion dense-phase region and circulating combustion technology of furnace upper portion rare-phasa region are discussed in the present paper. The circulating fluidized bed boiler, based on the above-cited technology, has the following advantages: high efficiency, small space, low cost, light wear, low power consumption, stable and simple operation and a wide range of load adjustment capability as well as a high adaptability to the burning of various coals. In view of the foregoing it pertains to an ideal type of industrial circulating fluidized bed boiler. Its long-term operation has proved that the multiple in-furnace circulating combustion technology is ideally suited for industrial circulating fluidized bed boilers of small and low-height combustion space. Key words: CFBC boiler, combustion technology, circulating combustion, structural optimization

加旋流化床颗粒扬析规律的试验研究＝ An Experimental Study of the Elutriation Mechanism of Vortexing Fluidized Bed Particles[刊，中]/Liu Kunlei, Jin Baosheng, Zhao Changsui, et al (Southeastern University)// Journal of Engineering for Thermal Energy & Power. -1995,10(3). -162-167

With the fly-ash falling off from a fluidized bed serving as test material a systematic study of the elutriation mechanism of fluidized bed particles was conducted on a vortexing fluidized bed test stand with a cross-section area of 0. 285m × 0. 285m, a height of 6 m and heat input of 0. 3 MW. The test results have shown that the elutriation rate constant of the paticles in the vortexing fluidized bed is considerably lower than that of a conventional bubble bed. However, there exists a great difference between the elutriation behavior of fly-ash in the vortexing fluidized bed of rectangular section and that of glass balls in a vortexing bed of circular section. Under the same particle size and operating conditions the former has a significantly greater elutriation constant than the latter. The separation characteristics of the secondary air in the vortexing fluidized bed supension space is also somehow different from that in a cyclone separator. Key words: fluidized bed boiler, coal, particle, elutriation rate

关于齿轮磨合运转工况的研究＝A Study on the Running-in Operating Mode of Gears[刊，中]/Zhao Jianping, Du Hongjia (Harbin Shipbuilding University)//Journal of Engineering for Thermal Energy & Power. -1995, 10(3). -168-174