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炉管泄漏的声学特性研究

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摘 要: 电站锅炉换热器高压蒸汽管路泄漏的声学监测是故障早期发现的重要手段, 对于合理安排维修时间和提高设备的利用率具有十分重要的意义。文中对较小尺度泄漏孔喷流噪声的特性进行了理论分析和实验研究, 对实测喷流噪声信号进行了频谱分析和特征提取。分析结果表明, 喷流噪声的自相关功率谱密度分布表现出明显的峰值现象, 峰值频率随着喷口尺度的增大而降低。对于压力比低于临界压力比的欠膨胀小孔喷流, 当喷口尺度从 1 mm 到 4 mm 时, 噪声功率谱的峰值 Sr 数从 0.05 到 0.13, 这一特点可用于估计泄漏喷口的尺度。同时, 根据高温蒸汽小孔喷流的功率谱分布状态, 对信号滤波提出了建议。

关 键 词: 电站锅炉; 炉管; 声学监测; 喷流噪声; 频谱分析; 功率谱;

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引 言

电站锅炉水冷壁、过热器、再热器和省煤器等承压换热器的"四管"爆破现象是影响电站锅炉安全、经济运行的重要问题, 在电站设备的运行故障中占有很大的比例。有些锅炉换热器爆管频繁, 甚至不得不降低主汽温度运行, 对机组经济性造成很大影响[1]。采用声学监测的方法可以早期发现炉管泄漏故障, 从而进行适时维修, 防止泄漏扩大损坏其它管路和造成更大破坏, 提高设备的可利用率, 减少经济损失。声学监测方法是利用声传感器和信号处理专家系统来检测管道泄漏, 可以给出监测结果而且能够确定泄漏口的大小及位置, 是一种比较实用的检测方法[2], 得到了较多的应用。声学监测系统主要由声学信号采集系统和信号处理专家系统组成, 其报警的灵敏程度和对泄漏现象识别的智能程度, 通常依赖于对专家系统的提前训练。因此研究锅炉承压管路泄漏噪声的声学特性是提高管道泄漏监测水平的重要内容。本文主要研究炉管泄漏噪声的声学特性, 分析喷流噪声的频谱特征从而推断喷流孔的几何特征, 通过理论分析和实验研究建立识别喷流孔状态的依据。

1 喷流噪声的声学特性

电站锅炉换热器是高温高压的换热设备, 当发生炉管泄漏时, 会形成高速喷流, 流速接近当地声速, 同时换热器外、内压力比低于临界压力比 $v_{cr}=\left(2/(k+1)\right)^{\frac{k}{k-1}}$, 喷流孔出口处的气流处于欠膨胀状态。以一般的电站锅炉过热器为例, 假设过热器内的压力为 14 MPa, 温度为 530 ℃, 则将泄漏喷口视为渐缩喷口且为可逆定熵流动时, 出口截面压力为 7.644 MPa, 温度为 426.24 ℃, 焓降为 189.368 kJ/kg, 出口流速可达 615 m/s。由于喷口形状的不规则性和过程不可逆性, 实际出口速度应该略低于该值。对于直径为 d 的圆形喷口的淹没射流, 可将射流沿流动轴线划分为 3 个部分[3]: 自出口至 4～5d 区间为起始段, 产生的噪声以高频为主; 5～15 d 区间为过渡段, 噪声中的低频成分逐渐增加; 15 d 之后为主流段, 流域很宽, 流速降低, 产生的噪声以低频为主。喷口处于欠膨胀状态的喷流噪声也称为阻塞噪声, 要比喷口处于完全膨胀状态的喷流噪声更强烈。

由于高速喷流的湍流漩涡在尺度和强度上连续发展, 喷流噪声具有宽频特征[4], 喷流远声场的噪声谱是连续的带有微弱的最大值, 当测点与喷流轴线方向之间的夹角减小时, 噪声谱上的低频成分略有增加, 而且噪声谱的最大值表现更加明显[5]。喷流的出口流速提高, 噪声谱中的高频成分增加; 喷口的直径扩大, 则噪声谱中的低频成分增加。有关大量实验表明, 喷流的声功率谱取得极值所对应的斯特劳哈数($Sr=fd/u$, 其中 f 为频率, s^{-1}; d 为喷口直

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径, m; u 为喷口平均流速, m/s)区间为 0.2~0.5[5]。不过, 这些实验采用的喷口尺度通常在数厘米以上。对于锅炉特定区域的炉管泄漏, 可以认为在一定工况范围内泄漏孔出口流速是确定的, 取决于临界压力比和泄漏前的温度。这样, 如果能够给出谱密度峰值对应的 *Sr* 数的规律和测定峰值频率 *f*, 则可以估计喷口直径 *d*。

莱特希尔(Lighthill)分析了喷射紊流的发声问题, 得出喷流噪声强度与气流速度和喷流口径之间的关系, 这就是著名的"八次方定律"。对于高亚音速的喷流噪声, 总的声功率可以表示为:

$$W = k_0 \frac{\rho^2 u^8 d^2}{\rho_0 c_0^5}$$

式中: W—喷流噪声总功率; k_0—实验系数; ρ、u、d—喷口处流体的密度、流速和喷口直径, $\rho_0 c_0$—环境声阻抗。由于在一定的工况下, 特定区域的炉管泄漏喷流速度基本上是确定的, 因此噪声总功率表现为和喷流口特性尺度的平方成正比。

2 喷流噪声信号的采集

喷流噪声的信号采集装置包括声源和信号采集系统。其中信号采集系统为 BSWA VS302 USB 便携式双通道声学振动分析仪, 由传声器、前置放大器、信号调理器、采集卡和计算机组成。同步采样, 精度 16 bit, 最大采样率 48 kHz。声源则是采用在空气压缩机的压力容器出口安装不同直径的喷口形成。

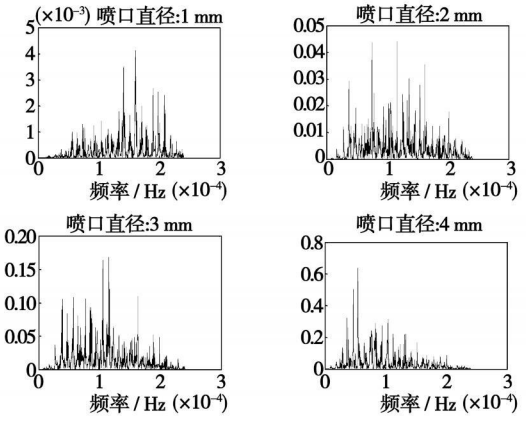

图 1 喷流噪声的功率谱

实验在安装有消声壁面的声学实验室中进行, 分别对口径为 1、2、3 和 4 mm 的喷流噪声进行了数据采集和处理, 传声器至喷流孔的直线距离为 3.85 m, 传声器与喷流孔之间的连线与喷流轴线之间的夹角为 30°。采集噪声信号时压力容器内的空气表压力在 0.5~0.8 MPa, 容器外、内压力比小于临界压力比。容器内外温度均为 20 ℃。由于喷口较小, 不便安装流速测量装置, 对出口流速采用估算数值。按渐缩喷口可逆流动获得喷口流速为 313 m/s, 考虑不可逆性取喷口流速为 300 m/s。

如果采用蒸汽喷流可以获得更为直接的结果, 不过采用压缩空气的喷流噪声实验是可行的, 因为尽管相同喷口尺度的蒸汽喷流和空气喷流频谱各异, 但其谱密度沿斯特劳哈数的分布是一致的。

计算机采集的是离散的由声压信号转换的电压信号, 采样频率为 48 kHz, 因此频谱分析的最大频率是 24 kHz。

3 噪声信号处理

对采集的离散时间序列噪声信号 $x(n)$进行频谱特征分析。首先对信号 $x(n)$做快速傅里叶变换(FFT)[6]:

$$X(k) = \sum_{n=1}^{N} x(n) \cdot e^{-j2\pi(k-1)\left((n-1)/N\right)},$$

$k = 1, 2, \cdots, N$

式中: N—傅里叶变换的点数, 决定频谱分析的分辨率, 取为 1 024 点。噪声信号的功率谱为:

$$P(k) = \frac{X(k) \cdot \mathrm{conj}(X(k))}{N},\ k = 1, 2, \cdots, N$$

$P(k)$中的前 $N/2+1$ 个点表示功率谱分布, 其余为冗余。功率谱序列和频率 f(Hz)的对应关系为:

$$f = Fs \cdot (k-1)/N,\ k = 1, 2, \cdots, N/2+1$$

式中: Fs—采样频率, 实际的功率谱为 $P(f)$, 4 组信号的功率谱如图 1 所示。可以看出, 功率谱变化的规律是随着喷流口径的增大, 噪声中的低频成分逐步增加。尽管喷流噪声的功率谱是宽频的, 但能量明显集中在一定的频率范围且有极大值, 只是极值点不易确定。为此, 采用 Yule—Walker 算法对信号进行二阶自回归处理, 获得信号的功率谱密度如图 2 所示。噪声信号的自回归功率谱密度具有明显的峰值, 不同喷流口直径时自回归功率谱密度峰值点所对应的频率 f_{max} 随着喷流孔直径的增大而减小, 峰值点所对应的斯特劳哈数 Sr_{max} 也有变化, 在实验范围内, Sr_{max} 随着喷流口直径的增大而逐渐增大。具体数值如表 1 所示。

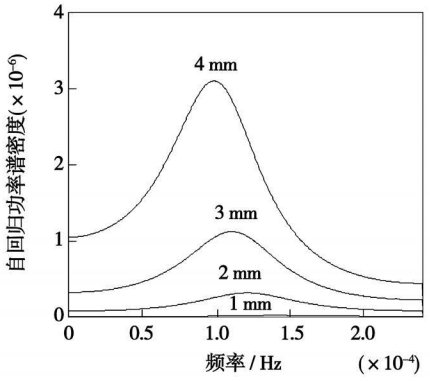

图 2　喷流噪声的 AR 功率谱密度

表 1　喷流噪声特性

孔径/ mm	f_{max}/ kHz	Sr_{max}	f_{max-w}/kHz	峭度
1	14.016	0.05	28.02	3.014
2	12.14	0.08	24.27	3.038
3	11.109	0.11	22.22	2.92
4	9.8906	0.13	19.79	2.56

因此, 对于早期炉管泄漏的喷流噪声, 可以根据其自回归功率谱密度的峰值对应的 Sr_{max} 的变化趋势分析泄漏孔的变化, 同时根据峰值斯特劳哈数和峰值频率的数值来估算喷流孔的孔径, 即 $d = Sr_{max} \cdot u / f_{max}$。对于过热蒸汽的喷流, 假设 Sr_{max} 的特性相同, 则当喷流口出口流速为 600 m/ s 时, 喷流噪声自回归功率谱密度的峰值频率在表 1 中以 f_{max-w} 给出, 其中喷流孔直径为 3 和 4 mm 的计算结果和文献[7] 中采用过热蒸汽进行的喷流噪声实验结果相吻合。

对采集的时域信号样本进行的峭度分析表明(如表 1 所示), 喷流孔直径从 1 到 3 mm, 样本数列的峭度变化不大, 接近于正态分布的 3。喷流口进一步增大时, 样本数列的峭度值降低。

实验研究是在静止介质中进行的, 对于锅炉烟道, 烟气的流动对声音的传播有一定影响。由于烟道内声速较高, 传声器与声源连线方向的烟气流速相对较低, 因此可以不计烟气流动对噪声频谱特性的影响。

4　结　论

锅炉换热器高压蒸汽管路泄漏的声学监测是电站锅炉设备爆管故障早期发现的重要手段, 尽早发现泄漏现象、估算泄漏孔的大小和评估泄漏孔的发展状况, 对于合理安排维修时间、避免故障扩大和提高设备的利用率具有十分重要的意义。

本文对泄漏孔喷流噪声的特性进行了理论分析和实验研究, 对实测喷流噪声信号进行了频谱分析和特征提取。结果表明, 噪声信号的自回归功率谱密度具有明显的峰值。和其它较大喷口尺度喷流实验的结果略有不同, 在较小喷口尺度(直径或当量直径从 1 到 4 mm)条件下, 噪声信号功率谱密度的峰值对应的斯特劳哈数大约在 0.05 ~ 0.13 之间, 其变化规律可用于泄漏孔尺度的估计, 同时提取功率谱峰值频率和计算泄漏喷流速度加以核算。由于锅炉设备运行时会产生很大的背景噪声, 泄漏噪声淹没其中, 不过, 像燃烧、烟气横掠管路以及机械噪声等背景噪声都具有低频特性。本文的计算表明, 4 mm 以下尺度的高温蒸汽喷流噪声的峰值频率在 19.79 kHz 以上, 在对噪声信号进行滤波处理时应该予以考虑。由于计算机处理水平的提高, 同时给出多种处理结果是可行的, 其中滤除 15 kHz 以下噪声的滤波处理会有助于泄漏现象的早期发现。

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(编辑　滨)

·书　讯·

《锅炉用水和冷却水中油含量的测定》

该书介绍了锅炉用水和冷却水中油含量的测定方法, 还介绍红外光度法适用于锅炉给水、生产返回水及化工设备冷却水中油含量为 0.1 ~ 100 mg/ L 的测定, 同时也适用于其它水样中油含量的测定; 紫外分光光度法适用于火力发电厂锅炉给水、生产返回水及化工设备冷却水中油含量为 0.1 ~ 4.0 mg/ L 的测定。读者对象: 钢铁、化工生产企业锅炉用水标准化技术部门、检测单位相关技术人员。

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flecting in-furnace combustion conditions were obtained by utilizing computer-based image processing technology. The detection tests of in-furnace radiant energy characteristics were carried out at two stable loads, 300 MW and 250 MW, featuring oxygen-content variation conditions. The test results show that there exists a good negative correlation between the radiant energy and oxygen-content signal with the absolute value of the negative correlation coefficient at a low load being higher than 0.9. The change of radiant-energy signal emerged in advance of that of the oxygen content with the time in advance being 30 to 40 seconds. **Key words**: coal-fired boiler, radiant energy, variable oxygen content, characteristic detection, correlation analysis

渐近线型污垢生长的参数特性及测量方法=**Parameter Characteristics and Measurement Method for Asymptotic Type Fouling Growth**[刊, 汉] / LENG Xue-li, TIAN Mao-cheng, PAN Ji-hong, FAN Ming-xiu (College of Energy Source and Power Engineering, Shandong University, Jinan, China, Post Code: 250061) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(3). —278 ~ 279

In the light of the specific features of asymptotic type functions, analyzed were the characteristics governing the time constant of asymptotic type fouling growth and the fouling heat-resistance asymptotic value. It is noted that the fouling time constant is in inverse proportion to the logarithm of the ratio of the fouling growth rates obtained from two measurements, and in direct proportion to the time interval of two measurements. The fouling heat-resistance asymptotic value can be expressed by the fouling heat-resistance and fouling growth rate obtained by the second-time measurement and the fouling growth rate obtained by the first-time measurement. The method under discussion can be used to obtain the time constant and heat-resistance asymptotic value of the asymptotic type fouling in its growth process, thus saving experiment time. It is an improvement on the heat-resistance method for measuring fouling growth process and at the same time is suitable for the forecast of asymptotic type fouling growth process. **Key words**: fouling parameter, measurement method, forecast method

半焦气力输送模型及在煤拔头中试装置中的应用=**A Semi-coke Pneumatic Transmission Model and its Applications in a Coal-topping Pilot Plant**[刊, 汉] / ZHAO Guang-bo, ZHAO Dan-ni, QIN Ming, WANG Wen-yu (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(3). —280 ~ 284

A one-dimensional mathematical model was established for a semi-coke pneumatic transmission system. In this connection, a variety of semi-coke pneumatic transmission processes were taken into account. They include: solid particle movement, convection and radiation heat exchange between gas and solid, precipitation and combustion of residual volatile component in semi-coke, combustion of coke, reduction of CO_2 on the coke surface and combustion of CO in gas phase etc. The pilot plant of coal topping and its systematic configuration were described, and the model thus established was used to numerically simulate the material transmission and distribution system. A variety of parameters in the semi-coke transmission process were obtained, including sectional gas-solid average speed, en route pressure loss and gas-solid two-phase temperature etc., providing guidance for the running of the pilot plant. The calculation results show that in the semi-coke pneumatic transmission process, the combustion of coke can be neglected. The combustion of volatile component can lead to an increase of gas temperature from 180 ℃ to 800 ℃. An increase of gas speed will increase the pressure loss. In the meanwhile, it can also result in a serious wear and tear of pipes. Hence, a variable tube-diameter transmission method is recommended for the pilot-plant test. **Key words**: coal topping, semi-coke, pneumatic transmission, numerical simulation

炉管泄漏的声学特性研究=**A Study of Acoustic Characteristics of Leakage from Boiler Tubes**[刊, 汉] /ZHANG Xiao-dong (College of Energy Source and Power Engineering, North China Electric Power University, Beijing, China, Post Code: 102206), CHEN Dong-hui (Clyde Bergemann Huatong Material Handling Co. Ltd., Beijing, China, Post Code: 100035), DU Yun-gui (CPI Yuanda Environmental Protection Engineering Co. Ltd., Chongqing, China, Post Code: 400060) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(3). —285 ~ 287

Acoustic monitoring of leakage from HP steam pipelines of utility—boiler heat exchangers is an important means for early fault detection and is of major significance for the rational arrangement of maintenance schedule and the enhancement of equipment availability. A theoretical analysis and experimental study were conducted of the jet flow noise from a relatively small leakage hole. A spectrum analysis and characteristics pick—up were performed of the jet flow noise signal actually measured. The analytic results show that the self—correlated power spectrum density distribution of the jet flow noise exhibits an obvious peak—value phenomenon and the peak—value frequency will decrease with an increase of the jet—flow hole diameter. For an under—expanded small hole jet flow at a pressure ratio below the critical one, when the jet—flow hole diameter increases from 1 mm to 4 mm, the peak value of the noise power spectrum Sr number will go up from 0.05 to 0.13. Such a feature can be used to estimate the leakage hole size. In the meanwhile, a proposal has been made for signal—wave filtering on the basis of the power spectrum distribution of high—temperature steam small—hole jet—flows. **Key words**: acoustic monitoring, jet flow noise, spectrum analysis, power spectrum

火电机组辅助汽水强度矩阵的研究及其应用=**A Study of Auxiliary Steam—water Intensity Matrix in a Thermal Power Plant and its Applications**[刊, 汉] / YAN Shun—lin, WANG Jun—you, LI Yong—hua (College of Energy Source and Power Engineering, North China Electric Power University, Baoding, China, 071003) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(3). —288 ~ 292

An auxiliary steam—water system is an important integral part of the thermodynamic system in a thermal power plant. It is of major realistic significance to analyze the influence of the system in question on the coal consumption rate in power generation. However, the traditional thermal—economy calculation methods all have its limitations to some extent. In the light of the shortcomings of the currently prevailing calculation methods, an auxiliary steam—water intensity matrix for thermal power plants has been proposed. Through specific case calculations of typical thermal power plants with different installed capacities, it can be shown that the calculation model does not need to establish an energy conservation and mass balance equation for the thermodynamic system, enjoying such specific features as small calculation work load, simple and quick calculation, high calculation accuracy and great versatility. The model can provide a new tool for attaining energy savings and energy consumption reduction of thermal power plants, especially for performing a quantitative analysis and calculation of the auxiliary steam—water system. **Key words**: auxiliary steam—water, intensity matrix, coal consumption rate, energy saving and consumption reduction

不同进口形式方形分离器的试验研究=**Experimental Study of a Square—shaped Separator with Different Inlet Forms**[刊, 汉] / ZHENG An—qiao, SU Ya—xin, WAN Xin (College of Environment Science and Engineering, Donghua University, Shanghai, China, 201620) // Journal of Engineering for Thermal Energy & Power. — 2008, 23(3). —293 ~ 297

By changing the steam inlet forms of a separator, an experimental study has been conducted of the performance of a square—shaped separator. The results of the study indicate that the cut particle diameter of various separators decreases with an increase of inlet air speed (see Fig. 5) and with an increase of the particle concentration at the inlet, the particle diameter first decreases and then increases (see Fig. 7 and 9). The drag forces of various separators increase with an increase of the inlet air speed (see Fig. 6) and decrease with an increase of the inlet particle concentration (see Fig. 8 and 10). With respect to separation characteristics, the single inlet form of tangential direction is better than the double inlet form of the said direction; the double inlet form of oblique tangential direction is superior to the single inlet form of the said direction. The inlet form of the tangential direction is better than the inlet of the oblique tangential direction. As for the drag forces, the double inlet form of the tangential direction is better than the single inlet form of the aforementioned direction; the single inlet form of the oblique tangential direction is superior to the double inlet form of the said direction and the gas inlet form of the oblique tangential direction is better than that of the tangential direction. The research results can provide an underlying basis for the structural optimization design of square—shaped separators. **Key words**: circulating fluidized bed, separator, square—shaped cyclone separator, separation mechanism, separation efficiency