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电站凝汽器铜管的视情更换原则

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摘 要: 基于 RCM 定性分析和维修性分析, 确定了电站凝汽器合理的维修方式。通过维修方式决策, 选取了成批更换模型, 建立了凝汽器铜管视情更换的定量分析模型, 研究了凝汽器铜管视情更换状态参数的选择原则。以 200 MW 机组 N－11220－4 型凝汽器为研究对象进行了实例研究, 对现行维修规程提出了相应的修改建议。研究结果表明, 当水质偏离设计工况不严重时, 可以选取累积堵管率作为视情更换的状态参数, 决策阈值为 1.28%; 当水质偏离设计工况严重时, 可以选取累积堵管次数和当年故障率作为状态参数, 决策阈值为累积故障次数达到 20.4, 并且当年故障率达到 3.95 次/年; 与现行维修方式相比, 优化后的维修方式能降低运行与维修成本 34%。

关 键 词: 电站凝汽器; RCM 分析; 维修决策; 视情更换
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1 前 言

电站凝汽器的主要故障是铜管泄漏, 故障发生后需要停机或减负荷才能排除, 单次故障造成的损失就较大。由于铜管数量大, 故障率相对较高, 所以凝汽器役龄内的故障费用较高。同时, 因为铜管数量大, 购置费用较高, 使得预防性整体更换的费用也较高。因此, 研究合适的铜管整体更换原则, 具有重要的工程意义, 可降低发电厂运行与维修成本。

现有《检修规程》中凝汽器铜管整体更换的原则存在以下不足: 重视预防维修材料费用对运行与维修成本的影响, 忽略了故障造成的损失对运行与维修成本的影响; 考虑了实施视情更换的必要性, 但未给出便于操作的状态参数决策阈值。

本文通过 RCM 定性分析和维修性分析, 确定了凝汽器合适的维修方式, 分析了现行检修规程存在的问题。根据维修方式决策, 选择了合适的维修优化模型, 即成批更换模型。使用所建模型, 研究了凝汽器铜管视情更换的决策原则。以 200 MW 机组 N-11220-4 型凝汽器为研究对象, 进行了实例研究。最后, 给出了电站凝汽器检修规程的修改建议。

2 电站凝汽器维修优化问题概述

2.1 RCM 定性分析

RCM 理论用系统工程的分析方法为维修需求分析提供了两个基本工具, 即 FMEA 和 LTA。FMEA 的目的在于分析故障后果的类型和故障发展规律, LTA 的目的在于分析预防性维修的必要性和预防维修的工作类型[1]。电站凝汽器的 RCM 定性分析结果见表 1。可见, 电站凝汽器有必要进行预防维修, 预防维修合适的的工作类型为视情维修。

表 1 电站凝汽器 RCM 定性分析结果

分析项目		分析结论
FMEA	主要故障	铜管泄漏, 导致凝结水质不合格
	故障原因	磨损、腐蚀
	故障后果	机组减负荷或停运
	故障后果类型	使用性后果
故障发展规律		故障由磨损、腐蚀引起, 故障率随时间递增。
LTA	预防维修必要性	故障后果为使用性后果, 且故障率随时间递增, 有采取预防性维修措施的必要。
	预防维修工作类型	视情维修
	适用性准则的吻合性分析	可以用堵管率或故障率作为定义潜在故障的指标, 从潜在故障发展为功能故障(不能实现设计换热量)的时间大于一个大修周期。

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2.2 合理的维修方式分析

维修方式是指在各类维修时机上，采取何种维修活动，以及按何种原则安排预防维修活动。维修方式决定了役龄内各种维修活动的发生次数，从而决定了维修决策分析中效用函数的算法。维修方式是选择维修优化模型类型的依据，役龄内可能的维修活动取决于设备的维修性基本特性。

电站凝汽器的维修性基本特性如下：(1)故障铜管无法修复；(2)铜管可以局部切除：堵管；(3)铜管可以按区域进行局部更换，但因中间有多块管板，从两端管板操作工艺繁琐，耗时多、易失败，失败后只能堵管；(4)铜管整体更换可以从内部操作，工艺简单；(5)更换铜管会造成管孔损伤，为了控制铜管胀口泄漏率，凝汽器役龄内只能整体更换铜管一次。

针对凝汽器铜管，可能采取的维修活动包括：局部切除、局部更换和整体更换。

电站凝汽器的维修时机包括 3 类：凝汽器故障停运；机组小修；机组大修。

在凝汽器故障停运时，为了尽快恢复设备运行，合适的维修作业为局部切除。在机组常规大、小修中，对腐蚀、磨损严重的铜管可以按局部区域进行更换，合适的维修活动类型为局部更换。在机组特殊大修中，当凝汽器铜管劣化程度严重时，可以进行预防性整体更换，合适的维修活动类型为整体更换。

因此，电站凝汽器合理的维修方式为：运行中发生故障时，进行局部切除；设备劣化程度不严重时，在机组常规大、小修中安排常规项目：局部更换；当设备劣化程度严重时，在机组大修中安排整体更换。

2.3 现行检修规程存在的问题分析

电站凝汽器现行维修方式基本合理，但铜管整体更换原则需要优化。

现有的检修规程规定，当出现以下情形之一时，铜管进行整体更换：(1)当堵管率达到 10%以上时；(2)当水质严重偏离设计标准，铜管腐蚀严重时。

第一项规定的依据是相对于额定换热量而言，设计的换热面积有 10%的冗余。该规定的决策原则是在可实现规定功能的前提下，最大限度地利用铜管的有效寿命。该规定将铜管整体更换安排在设备丧失规定功能之后，维修工作的实质是事后维修，而不是预防维修。运行与维修成本中包含预防费用和故障费用。该规定基于以下考虑：更换间隔过短，役龄内的平均预防费用将上升。在重视预防费用对运行与维修成本的影响时，该规定忽略了故障费用对运行与维修成本的影响：随役龄增加，铜管劣化，单位时间内系统停运次数递增，故障损失折算费用递增。因此，为了兼顾故障费用和预防费用，需要在凝汽器还能实现其规定换热功能之前进行预防性整体更换。

第二项规定重视设备劣化程度对平均故障费用的影响，考虑了实施视情维修的必要性。但该规定没有给出客观的、量化的控制指标，实际操作中需要人主观判断设备的健康状况，操作过程随意性较大。

可见，凝汽器维修优化的任务是通过优化模型确定视情更换的决策原则。

3 凝汽器维修优化模型

3.1 优化模型类型选择

凝汽器铜管役龄内经历的 3 类维修活动对设备状态具有以下影响：(1)故障时局部切除少量铜管，能恢复设备功能，但不会改变铜管整体的故障率，维修活动为最小维修；(2)常规大、小修中，局部更换少量铜管对整体的故障率影响较小，维修活动也可近似认为是最小维修；(3)铜管整体更换后，整体“修旧如新”，维修活动为完全维修。

役龄内，研究对象经历多次最小维修、一次完美维修，其维修方式符合选择成批更换模型的要求[2]。因此，选择成批更换模型作为凝汽器铜管整体更换的定量分析模型。

3.2 维修/故障费用计算模型

为了综合考虑运行与维修成本中的预防费用和故障费用，凝汽器铜管整体更换决策问题的效用函数宜选择维修/故障费用。常规大、小修中的局部更换铜管为“陪修”，不影响系统可用率，材料、人工费用较小，可以忽略。根据成批更换模型的计算方法，凝汽器铜管整体的维修/故障费用包含故障费用和整体更换费用，按下式计算[3]：

$$C(T)=EXC_f(T)+EXC_p(T)=H(T)C_f+C_p \tag{1}$$

式中：T—整体更换时的累计运行时间；$EXC_f(T)$—役龄 T 内故障费用总和；$EXC_p(T)$—役龄 T 内预防费用总和；$H(T)$—风险函数，T 时间内的累积故障次数；C_f—一次故障维修的费用；C_p—铜管整体更换费用。

$$C_f=C_{fm}+ECF \tag{2}$$

式中：C_{fm}—故障维修的材料、人工费用；ECF—设备故障停运导致系统可用率下降产生的损失，计算方法见文献[4]。

由于选择在机组大修中进行预防性整体更换, 凝汽器预防维修费用中只含材料、人工费用, 即:

$$C_p = C_{pm} \tag{3}$$

式中: C_{pm}—预防性整体更换的材料、人工费用。

3.3　寻优约束条件

由于选择在机组大修中进行预防性整体更换, 所以最优间隔应满足以下约束条件:

$$T \in \left\{ T_j \mid T_j = \sum_{i=1}^{j} \tau_i \right\} \tag{4}$$

式中: τ_i—机组第 i 次与第 $i-1$ 次大修之间的间隔; T_j—机组第 j 次大修时凝汽器铜管的累计运行时间。

3.4　优化模型

考虑寻优约束条件后, 凝汽器铜管预防性整体更换的优化模型如下:

$$\begin{cases} \min\ c(T) = \dfrac{H(T)C_f + C_{pm}}{T} \\ S.T.\ \ T \in \left\{ T_j \mid T_j = \sum_{i=1}^{j} \tau_i \right\} \end{cases} \tag{5}$$

式中: $c(T)$—单位工作时间上的维修/故障费用。

4　凝汽器铜管视情更换决策准则

视情维修策略包括两个基本要素: 描述设备劣化程度的状态参数; 实施维修作业的决策阈值。

理论上, 优化模型式(5)的解就是通用的凝汽器铜管视情更换决策准则, 该准则的解析表达式为:

$$h(T) = \frac{H(T)}{T} + \frac{C_{pm}}{C_f} \tag{6}$$

式中: $h(T)$—风险率, 表示风险函数的变化率。

由于式(6)不便于工程应用, 需要选择合适的状态参数, 并研究便于操作的决策阈值。

由于工作环境, 即水质的变化, 对设备劣化速度和故障率有直接影响, 因此选择状态参数和决策阈值需要分别考虑水质稳定和水质恶化的情况。

与凝汽器健康状况相关的参数包括铜管磨损、腐蚀量, 累积堵管率, 累积堵管次数, 故障率。由于铜管数量大, 所以统计磨损、腐蚀量工作较为繁琐, 不便于实际操作。

选择累积堵管率, 即曾经被堵或更换的铜管数量占总数的百分比, 作为视情维修的状态参数具有以下优点: 该参数与设备的性能直接相关, 能用于定义功能故障状态, 也能代表铜管整体的劣化程度; 检修中该参数便于获得。但该参数作为状态参数具有以下缺点: 该参数不能直接反映水质变化对凝汽器故障费用的影响。

选择累计堵管次数和故障率作为视情维修的状态参数具有以下优点: 能够直接反应水质变化对故障费用的影响; 也能够反映铜管整体的劣化程度。因此, 该参数是合适的视情维修状态参数。

5　实例研究

为了获得工程上便于操作的决策阈值, 以 200 MW 机组 N—11220—4 型凝汽器为研究对象进行了实例分析。

5.1　对象特性

分析中采用的基本数据:

C_f: 20.2 万元; C_p: 640 万元; 铜管总根数: 17 000 根。

利用西北地区多台机组运行与维修历史数据, 经统计得到的累计故障次数和故障率见图 1, 不同役龄段上的堵管情况见表 2。

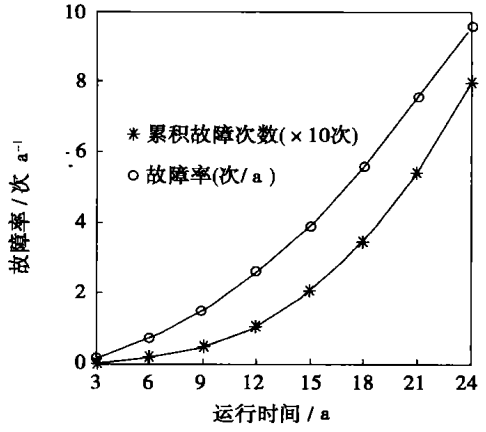

图 1　200 MW 机组凝汽器的风险函数和故障率

表 2　200 MW 机组凝汽器铜管在不同役龄段上的堵管情况

运行期间/a	每次故障平均堵管根数	期间末累积堵管根数	期间末累积堵管率/%
0~3	2.3	0.4	0
3~6	4.4	5.9	0.03
6~9	6.7	27.1	0.16
9~12	9.5	84.6	0.50
12~15	13.6	217.0	1.28
15~18	18.3	477.5	2.81
18~21	23.2	930.8	5.48
21~24	28.4	658.8	9.76

5.2 决策阈值分析

对应不同的更换周期，200 MW 机组凝汽器的平均故障费用和平均预防费用计算结果见图 2，平均维修/故障费用的计算结果见图3。

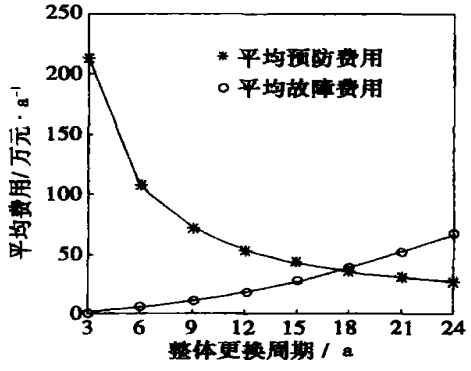

图 2 不同更换周期下，凝汽器的平均故障费用和平均预防费用

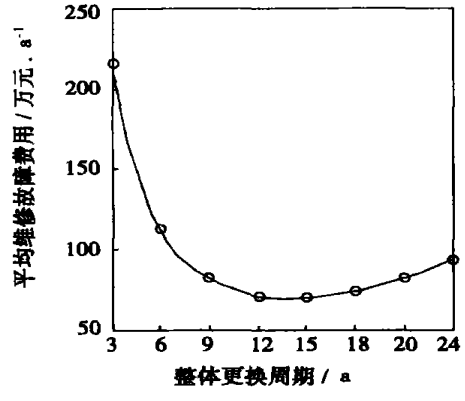

图 3 不同更换周期下，凝汽器的平均维修/故障费用

计算结果表明：

（1）按累积堵管率为 10%进行整体更换，更换间隔大约在24年左右。此时，平均预防费用降至24万元/年，但平均故障费用增加至 67 万元/年，平均维修/故障费用为 91 万元。该值不是最小值，累积堵管率10%不能作为决策阈值。

（2）更换间隔为 15 年，对应累积堵管率 1.28%，累积故障次数达 20.4，故障率 3.95 次/年。此时，平均维修/故障费用为最小值：70 万元/年；

（3）水质偏离设计值不严重时，决策阈值为累积堵管率 1.28%；

（4）水质偏离设计值严重时，决策阈值为累积故障次数达到20.4，并且当年故障率达到3.95 次/a。

5.3 现行维修方式和优化维修方式对比

现行维修方式和优化维修方式的分析结果对比见表3。结果表明，优化的维修方式能降低运行维修成本 34%。

表 3 200 MW 机组凝汽器现行维修方式与优化维修方式对比

	现行维修方式	优化维修方式
整体更换周期/a	24	15
整体更换时累积堵管根数占总数的百分比/%	9.76	1.28
整体更换时平均预防费用/万元·a^{-1}	24	43
整体更换时平均故障费用费用/万元·a^{-1}	67	27
平均维修/故障费用/万元·a^{-1}	91	70.0
整体更换时的累积故障次数	79.8	20.4
整体更换当年的故障率/次·a^{-1}	9.65	3.95
整体更换时累积堵管/根数	1 659	217

6 结 论

（1）现行检修规范中，凝汽器铜管整体更换原则（堵管率达 10%）没有考虑故障费用对运行维修成本的影响，存在严重的“维修不足”问题。

（2）当水质偏离设计值不严重时，可以选取累积堵管率作为决策阈值；当累积堵管率达到 1.28%时，凝汽器铜管应整体更换。

（3）当水质偏离设计值严重时，可以选取累积堵管次数和当年故障率作为决策阈值；当累积故障次数达到20.4，并且当年故障率达到 3.95 次/a 时，凝汽器铜管应整体更换。

（4）和现行维修方式相比，优化的维修方式能降低运行维修成本约 34%。

参考文献：

[1] MOUBRAY J. 以可靠性为中心的维修[M]. 北京：机械工业出版社，1995.

[2] MCCALL J J. Maintenance policies for stochastically failing equipment：a survey[J]. **Management Science**, 1965, **11**(5)：493－524.

[3] 陈学楚. 维修基础理论[M]. 北京：科学出版社，1998.

[4] 曹钟中. 电站给水泵组 RCM 定量分析方法的研究[J]. 中国电机工程学报，2003，**23**(9)：207－211.

（何静芳 编辑）

R113 Nucleate Boiling under a High Heat-flux Density[刊, 汉] /JIA Tao, DIAO Yan-hua (Postgraduate College of Chinese Academy of Sciences under the Engineering Thermophysics Research Institute of the Chinese Academy of Sciences, Beijing, China, Post Code: 100080)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —279 ~282

A R113 nucleate boiling experiment was conducted on a transparent ITO glass. During the experiment a high speed CCD (Charge Coupled Device) camera was placed under the ITO glass to take photos of the bubble images. The advantage of such a camera shooting consists in the elimination of the interference to the camera shooting caused by the merging of the fluid and bubbles. By the use of an image edge detection technique these bubble images were processed so that one can clearly see the boundaries of various bubbles in the bubble cluster, thus making it possible to correctly identify the quantity of bubbles. By taking account of the difference between the quantity of bubbles due to their merging and the quantity of nucleation sites under the bubbles, the actual magnitude of nucleation site quantity can be determined. Finally, a curve showing the variation of densities of the nucleation sites with heat-flux densities was plotted. **Key words**: nucleate boiling, image edge detection; nucleation site

纵向带突起内翅片管强化传热研究=**A Study of the Intensified Heat Transfer of Longitudinally Ridged Internal-finned Tubes**[刊, 汉] /WU Feng, LIN Mei, TIAN Lin, et al (State Key Laboratory of Power Engineering Multiphase Flows under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —283 ~286

Through experiments and numerical simulation methods a study has been conducted of the characteristics of convection heat exchange of ridged internal-finned tubes and a comparison of the above characteristics with the flow and heat transfer characteristics of straight internal-finned tubes performed. The experimental results indicate that the heat exchange characteristics of ridged internal-finned tubes are better than those of straight internal-finned tubes in terms of intensified heat transfer performance, but at the same time there is a corresponding increase in flow resistance. Through the adoption of a turbulent flow model capable of realizing $k-\varepsilon$ equation, the flow and heat transfer process of ridged internal-finned tubes have been simulated. The calculation results are in good agreement with the experimental ones. The calculation results indicate that the periodical ridges inside the finned tubes have changed the distribution of the inner-flow fields and temperature ones. Relative to the straight internal-finned tubes a secondary vortex flow has emerged, which is conducive to an intensified heat exchange and plays a definite destructive role to the flow boundary layer. Meanwhile, by increasing the turbulent kinetic energy of the flow field, the temperature gradient in the neighborhood of the heat exchange wall surfaces has been enhanced, contributing to an intensification of heat transfer. **Key words**: ridged internal-finned tube, forced convection, heat transfer characteristics, intensified heat transfer, secondary vortex flow

电站凝汽器铜管的视情更换原则=**Principles for On-condition Replacement of Copper Tubes in Power Plant Condensers**[刊, 汉] /CAO Zhong-zhong, GU Yu-jiong, YANG Kun (Education Ministry Key Laboratory of Power Plant Equipment Condition Monitoring and Control under the North China University of Electric Power, Beijing, China, Post Code: 102206)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —287 ~290

On the basis of RCM qualitative and maintainability analysis a rational maintenance mode is determined for power plant condensers. Through the decision-making of maintenance modes a batch replacement model has been chosen and a model for quantitative analysis of on-condition replacement of copper tubes in power plant condensers established. A study was conducted of the principles for choosing status parameters for the on-condition replacement of copper tubes in condensers. With the N-11220-4 type condenser of a 200 MW unit serving as an object of study a case study has been performed. Relevant proposals for revising maintenance regulations currently in force are put forward. The research results show that

when the water quality does not seriously deviate from the design regime, the accumulative tube-plugging rate can be chosen as the status parameter for the on-condition replacement with the decision-making threshold value being set at 1.28%. When the water quality deviates seriously from the design regime, the frequency of accumulative tube-plugging and the failure rate of the current year can be chosen as the status parameter with the decision-making threshold value being the accumulative failure frequency amounting to 20.4 times and the failure rate of the current year being set at 3.95 times/year. Compared with the currently prevailing maintenance modes, the optimized maintenance modes can reduce the operation and maintenance costs by 34%. **Key words**: power plant condensers, RCM analysis, maintenance decision-making, replacement based on specific conditions

内置稳燃热岛燃气锅炉内流动与传热数值模拟＝**Numerical Simulation in the Flow and Heat Transfer in a Gas-fired Boiler with a Built-in Stable-combustion Heat Island**[刊, 汉] /OU Jian-ping, MA Ai-chun (Energy Source and Power Engineering College under the Central South University, Changsha, Hunan, China, Post Code: 410083), LAI Chao-bin, DENG Ren-hua (Xinyu Iron and Steel Co. Ltd., Xinyu, Jiangxi, China, Post Code: 338001)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —291 ~294

With a gas-fired boiler provided with a built-in stable-combustion heat island serving as an object of study and by making use of CFD software PHOENICS coupled with the in-boiler fluid flow, combustion and heat transfer process, a numerical simulation analysis has been performed of the gas flow and heat transfer characteristics of the boiler. The impact of an ignition-aid burner operating condition and an annular stable-combustion heat island on the gas flow and heat transfer process in the boiler was studied with a comparison and verification being made in production practice. The results of the study indicate that the corner-tangential layout of the burners and the presence of an annular heat island in the boiler are conducive to the stable combustion and the formation of tangential flow modes in the boiler, enhancing the agitation of flue gases in the boiler and making the furnace temperature distribution more uniform. As a result, the heat exchange efficiency of the heating surfaces in the furnace has been improved. Through an adjustment of the location of ignition-aid burners the stable combustion of a low heat value gas-fired boiler has been realized. The research results can serve as a guide during the design improvement and production organization of blast furnace gas-fired boilers. **Key words**: boiler, blast furnace gas, stable combustion-based heat island, flow field, heat transfer, numerical simulation

燃油锅炉改烧瓦斯气炉内流动和燃烧过程的数值模拟＝**Numerical Simulation of the Flow and Combustion Process of an Oil-fired Boiler Being Converted to Burn Gas**[刊, 汉] /LIU Ya-qin, LI Su-fen (Power Engineering Department, Dalian University of Science and Technology, Dalian, Liaoning, China, Post Code: 116024), ZHANG Li (Dalian University, Dalian, Liaoning, China, Post Code: 116024)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —295 ~298, 302

An oil-fired boiler was converted to burn gas. To analyze the change of in-boiler flow and combustion conditions, the authors have conducted a three-dimensional numerical simulation by using software Fluent. A "Realizable $k-\varepsilon$" model was employed to simulate the turbulent flow with a swirling one, while a PDF model used for the simulation of turbulent flow combustion and a P1 model for the simulation of radiation. Through calculations the distribution of in-boiler flow field, temperature field and heat-flux densities along the height were obtained. The calculation results are of major theoretical significance for guiding the operation of gas-fired boilers and their modification. **Key words**: gas combustion, numerical simulation, flow field, temperature field, heat-flux density

超临界压力下水冷壁中间集箱分配特性的研究＝**An Investigation on the Flow Distribution Characteristics of a Water-wall Intermediate Header at a Supercritical Pressure**[刊, 汉] /ZHU Yu-qin, BI Qin-cheng, CHEN Ting-kuan