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高热流密度下 R113 核态沸腾中汽化核心密度的识别

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摘　要: 在透明的 ITO 玻璃上进行了 R113 的核态沸腾实验。实验中, 在 ITO 玻璃下放置了一个高速 CCD 摄像机用以拍摄气泡图像。这样摄像的优点是能够排除流体和气泡合并对摄像干扰, 然后运用图像边缘检测技术对这些气泡图像进行了图像处理。图像处理的结果能清晰地看到气泡群中各个气泡的边界, 从而准确地识别出气泡的数量。通过考虑由于气泡合并造成的气泡数量和这些气泡下面的汽化核心数量之间的差异, 得到了汽化核心数量的实际数值。最后绘制了汽化核心密度随热流密度的变化的曲线。

关　键　词: 核态沸腾; 图像边缘检测; 汽化核心

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1　引　言

核态沸腾是一种被工业界广泛应用的传热技术, 在冶金、化工、动力等领域有广泛的发展前景。其优点是能以较低的温差传递较多的热量。在核态沸腾中有相变发生, 相变发生的地方是成核地点[1], 称为汽化核心。汽化核心的研究对于核态沸腾技术的发展具有非常重要的意义。

传统的拍摄气泡图像的方法是从加热壁面的侧面拍摄[2~3], 这种方法在反映加热壁面上气泡动态特征的全面性和排除流体扰动对摄像的干扰方面均有一定的局限性。本文的实验装置中, 采用透明的 ITO 膜作为加热壁面, 将高速摄像仪放置在 ITO 加热壁面的下方摄像, 这种拍摄气泡图像方法的优点是能够全面地拍摄到加热壁面上气泡的动态特征和排除流体扰动对摄像的影响。

目前汽化核心的测量技术主要有两种: 一种是通过对反映加热壁面上的温度分布的红外图像进行分析得到汽化核心密度的数值。T. G. Theofanous 等人在 140 nm 厚的金属钛薄膜上进行了水的沸腾实验[4], 实验中将红外摄像仪放置在金属钛薄膜下方摄像, 得到了反映加热壁面上温度分布的红外图像。因为气泡生长时, 气泡底部微液层的蒸发使气泡底部壁面处的温度降低, 所以红外图像中较暗的圆点(暗点)即为气泡所在的位置。通过统计图像中暗点的个数就可以知道汽化核心数量的大小。这种方法的局限性是加热壁面必须非常薄, 这样才能保证拍摄到的红外图像能够较好地反映加热壁面的温度分布。另一种方法是识别实验中所拍摄到的加热壁面上的气泡图像中包含的气泡个数。但目前只能通过肉眼统计气泡图像中包含的气泡个数。这在热流密度较低的情况下是可以做到的, 但是当热流密度较高时, 气泡图像变得十分模糊和复杂, 仅凭肉眼观察非常困难。S. R. Yang 在进行一个不锈钢表面上的水的沸腾实验时就碰到了这样的困难[5]。图像处理技术是近几十年来蓬勃发展起来的一项技术。其优点是能够使我们从图像中获得很多有价值的信息, 而这些信息是无法通过肉眼观察得到的。图像边缘检测技术是通过检测图像中灰度发生突变的地方区分开图像中不同的个体。本文将图像边缘检测技术应用到 R113 池沸腾中拍摄到的气泡图像的图像处理中, 将高热流密度下气泡图像中组成气泡群的各个气泡区分开, 从而准确地识别出了气泡图像中包含的气泡个数, 在考虑了由于气泡合并(包括纵向合并和横向合并)造成的气泡数量和这些气泡下面的汽化核心数量之间的差异之后, 就可以得到汽化核心数量的实际值。

2　实验设备及过程

2.1　实验设备

实验系统如图 1 所示, 实验系统主要包括冷凝系统和沸腾系统。冷凝系统是用来冷却蒸汽的, 它包括冷凝管道和冷凝器。在实验过程中, 冷凝器使整个系统的压力保持为 0.1 MPa。沸腾系统包括: 沸腾加热槽, 辅助加热器和 ITO 加热膜。沸腾加热槽是一个

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长、宽、高分别为 140 mm、140 mm 和 250 mm 的不锈钢体。沸腾加热槽中有 4 个辅助加热器, 每个加热器的最大加热功率为 150 W。ITO 膜是一种透射可见光和导电的加热膜。它由氧化铟和金属锡组成。采用 ITO 膜作为加热壁面, 由于 ITO 膜是透明的, 可以从加热壁面下方直接观察到气泡的动态特征。ITO 膜的另一个特性是其电阻和温度之间呈线性变化。在实验前和实验后分别对 ITO 膜进行标定, 得到其电阻和温度之间的关系。在实验过程中记录下 ITO 膜电阻的变化, 就可以得到 ITO 膜的温度。为了在 ITO 膜上得到均匀的热流密度, 在 ITO 膜两端镀上了银电极。沸腾传热面是镀有 ITO 膜的玻璃, 固定在加热槽的底面。沸腾在 ITO 表面上产生。ITO 加热玻璃是个直径为 70 mm 的圆盘。实际的加热部分是一个长 30 mm, 宽 30 mm 的正方形薄膜(如图 2 所示)。为了保证沸腾换热只在该面积上产生, 只保留该面积上的 ITO 膜, 其余部分是酸蚀毛玻璃, 这种毛玻璃可以防止实验中液体从容器中遗漏出来。实验过程中利用电流表测量通过 ITO 膜的电流, 电流表的精度为 0.5%。利用数据采集系统(Agilent34970A)来测量 ITO 膜两端的电压, 其误差为 0.002%。利用所测得的电压和电流, 计算出 ITO 膜的电阻。实验中将高速摄像仪置于 ITO 加热玻璃下方, 这样摄像的优点是能够全面地观察实验中气泡的动态特征和排除由于流体扰动对摄像造成的影响。实验中采用微距镜头(AF Micro-Nikkor 60 mm f/ 2.8D)作为拍摄镜头, 其最大放大倍率为 1.0。

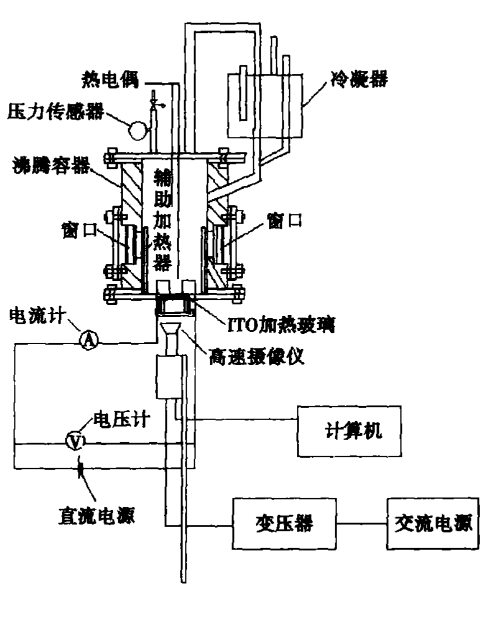

图 1 沸腾实验系统图

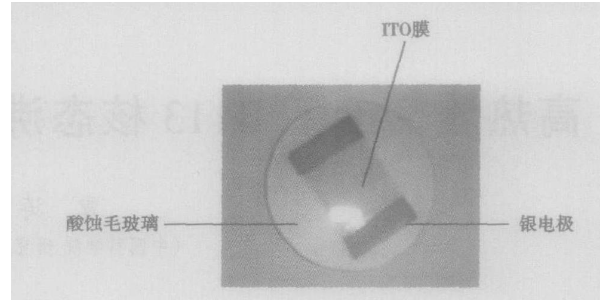

图 2 ITO 加热玻璃

实验中采用两只镍铬—镍硅热电偶来分别测量蒸汽和液体的温度, 热电偶的测量端直径为 0.5 mm, 其误差是 ±0.1 ℃。采用压力传感器来测量系统的压力, 其误差为 0.1%。

2.2 实验过程

(1) 首先要对沸腾槽中的液体工质进行除气。先将冷凝器的阀门拧紧, 将沸腾容器与真空泵通过真空管连接, 打开真空泵, 抽真空半个小时。抽真空后, 再灌入液体, 使液体水平面距沸腾加热面达到 120 mm 左右。随后打开冷凝器, 使沸腾换热容器与大气相同, 打开冷凝器的进水开关, 将 4 个辅助加热器全部打开, 调节辅助加热器的功率, 使容器内的液体达到充分发展的核态沸腾状态。整个除气过程持续 2 h 后关闭辅助加热器。

(2) 给 ITO 膜通电, 加热液体。在每一热流密度下, 加热状态持续 20 min。待系统稳定后, 记录 ITO 膜两端的电流和电压, 计算出 ITO 膜的电阻。在加热壁面上气泡产生之前, 加热功率的增加幅度是 1 W/ 次。当加热壁面上产生气泡后, 加热功率的增加幅度是 2 W/ 次。

(3) 将高速摄像仪打开, 同时打开光源, 调节三角支架的高度和镜头的焦距, 以便得到清晰的图像。调节好高速摄影仪的位置, 在每一个加热功率下开始拍摄。

(4) 实验结束后, 回收残余液体工质。

3 高热流密度下汽化核心数量的识别

对所拍摄到的气泡图像进行处理时采用的是边缘检测技术。从本质上讲, 图像边缘是图像局部特性不连续的反映, 它标志着一个区域的终结和另一个区域的开始。边缘检测首先检出图像局部特性的不连续性, 然后再将这些不连续的边缘像素连接起来就构成了边缘。对于一个数字图像, 通常使用微

分来描述像素灰度的不连续性。G_x 表示灰度沿 x 方向的微分, G_y 表示灰度沿 y 方向的微分。用 g 表示梯度:

$$g = (G_x^2 + G_y^2)^{1/2} \tag{1}$$

在对图像中的各像素进行微分运算时采用 3×3 像素的网格, 如图 3 所示。

z_1	z_2	z_3
z_4	z_5	z_6
z_7	z_8	z_9

z_i ($i=1,2,\cdots\cdots,9$) 表示灰度值

图 3　3×3 像素的网格

在对气泡图像进行边缘检测前先对图像进行中值滤波[6], 这样可以消除图像中的一些噪声。采用 sobel 边缘检测法对气泡图像进行识别[7], 式(2)和式(3)为 sobel 边缘检测算子在 x 和 y 方向的微分。

$$G_{x\_sobel} = (z_7 + 2z_8 + z_9) - (z_1 + 2z_2 + z_3) \tag{2}$$

$$G_{y\_sobel} = (z_3 + 2z_6 + z_9) - (z_1 + 2z_4 + z_7) \tag{3}$$

sobel 检测算子对应的梯度值为: g_sobel 为:

$$g\_sobel = [G_{x\_sobel}^2 + G_{y\_sobel}^2]^{1/2} \tag{4}$$

对于某一像素, 当 g_sobel 大于某一阀值时, 该像素为一边缘点。

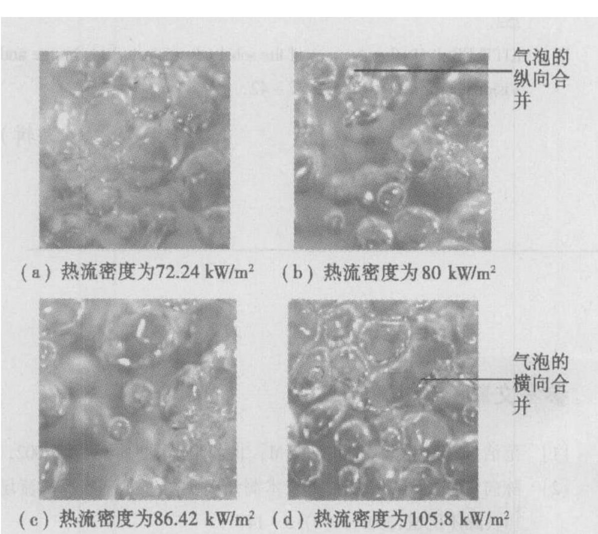

图 4　高热流密度下 R113 池沸腾中的气泡图像

图 4 为高热流密度下 R113 池沸腾中的气泡图像, 图 5 为对图 4 中的图像进行 sobel 检测的结果。从图 6 中可以清晰地看到气泡群中各个气泡的边缘, 从而区分开了气泡群中包含的各个气泡, 准确地识别出气泡群中所包含的气泡个数。但是气泡的数量并不等于这些气泡下面汽化核心的数量。这主要是由于气泡合并造成的。气泡的合并分为纵向合并和横向合并。当图像识别中识别出两个气泡, 但这

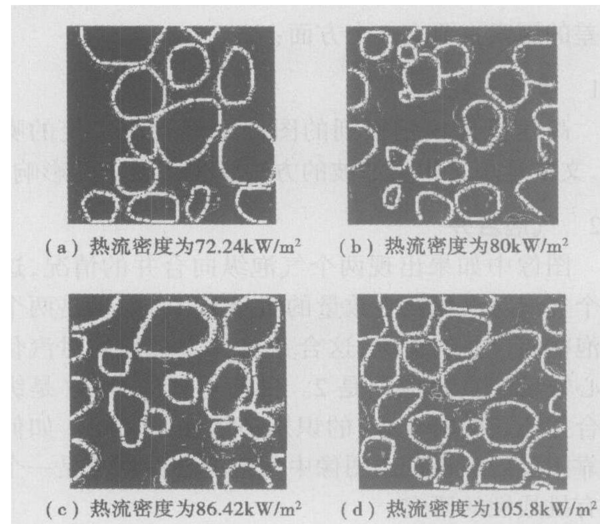

图 5　高热流密度下 R113 池沸腾中的气泡图像的边缘检测结果

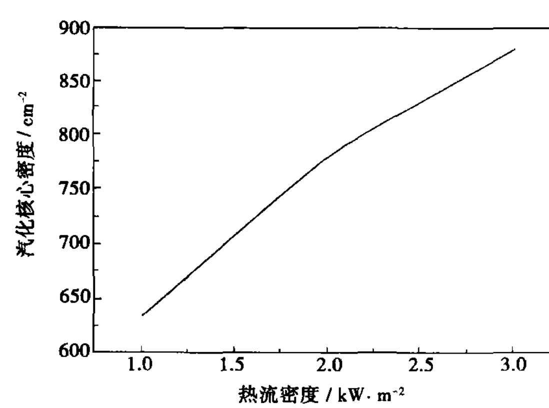

图 6　汽化核心密度随热流密度的变化

两个气泡发生了纵向合并(如图 5(b)所示), 其两个气泡对汽化核心数量的贡献为 1, 当图像识别中识别出一个气泡, 但这个气泡是由两个气泡横向合并而来的(如图 5(d)所示), 这个气泡对汽化核心数量的贡献应该为 2。值得提出的是, 气泡的合并情况只能通过拍摄到的气泡的时间序列来判断。这在目前还依赖于人肉眼的观察。实验中每个拍摄图像对应的实际拍摄面积为 2.05 mm^2。汽化核心的数量除以实际拍摄面积即为汽化核心密度。图 6 显示了汽化核心密度随热流密度的变化。

4 误差分析

导致由图像边缘检测技术识别汽化核心数量的误差的因素主要有 3 个方面:

4.1 噪音干扰

高速摄像仪拍摄到的图像中都含有一定的噪声,文中运用了中值滤波的方法减少了噪声的影响。

4.2 气泡合并

图像中如果出现两个气泡纵向合并的情况,这两个气泡对汽化核心数量的贡献是 1。如果是两个气泡横向合并的情况,这合并成一个气泡的对汽化核心数量的贡献应该是 2。目前对气泡合并(是纵向合并还是横向合并)的识别还依赖于肉眼。如何依靠图像处理识别出图像中气泡的合并情况是一个很有挑战性的研究。

4.3 图像边缘区域的影响

如图 4 所示,所拍摄到的气泡图像的边缘包含有一些不完整的气泡图像。这些边缘图像下面是否有汽化核心是一个较难判断的问题。如何定量地解决这一问题也是未来研究的一个重要方向。

5 结 论

(1) 从加热壁面底部拍摄气泡图像的摄像方法可以准确并且全面地捕捉到加热壁面上气泡的动态行为,并且消除流体扰动对摄像的干扰。

(2) 图像边缘检测技术可以使我们在高热流密度下能够较好地辨别出图像里气泡群中所包含的气泡个数。

(3) 气泡合并是造成气泡图像中包含的气泡数量和这些气泡下面的汽化核心数量之间存在差异的主要因素。先由图像边缘检测技术识别出气泡图像中包含的气泡个数后,然后再将上述因素考虑在内,就可以得到汽化核心的实际数量。

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(2) 不同类型的挡板、液柱流量、气体流速以及喷嘴与挡板的间距,对雾化液滴的尺寸和液滴运动速率都有较为明显的影响;

(3) 选用圆钢挡板,增大气体流速,减小喷嘴与挡板的间距有利于增强液柱的雾化效果,即雾化液滴尺寸减小,液滴运动速率增大;

(4) 增大液柱流量,虽不可减小雾化液滴尺寸,但液气比及液滴运动速率增大,有利于提高脱硫效率;

(5) 液柱冲击塔内的雾化液滴粒径遵循 Rosin-Rammler 分布,根据实验数据,可以得到各种实验工况条件下相应的液滴颗粒粒径 Rosin-Rammler 分布参数 n、$\overline{d}$,从而确定粒径分布特征。

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the standing-wave acoustic field has been derived. By combining experimental measurements with an advanced microscopic high-speed photography technique, the movement trajectory of a single micron-grade particle has been successfully photographed. Through an analysis of the pictures the required parameters were obtained. By way of seeking a solution the diameter and slippage factor of a single particle were obtained, avoiding a slippage assumption based on experience in the calculation process. The experimental and calculation results show that the present experimental platform can be used to measure micron and sub-micron grade single particle size as well as to observe and record dynamic characteristics. The acoustic entrainment method, being supported by a reliable theoretical basis, can serve as a new and feasible method for the measurement of micron-grade single particle size. **Key words**: micron, acoustic wave entrainment, microscopic photography, particle size measurement

数值研究扩散式旋风分离器流场与颗粒分离特性＝**Numerical Study of the Flow Field and Particle Separation Characteristics for a Diffusion Type Cyclone Separator**[刊, 汉] /TAN Xiao-jun, CHEN Li-hua, LI Hong-jian, et al (Mechanical and Energy Engineering College under the Zhejiang University, Hangzhou, Zhejiang, China, Post Code: 310027)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —270～274

With respect to a diffusion type cyclone separator in a gas/solid separation device, a RNG $k-\varepsilon$ turbulent-flow model and discrete-phase random trajectory model were adopted respectively to perform a numerical simulation of its inner flow field and particle separation behavior. The trajectory of particles with different diameters at a constant flow speed was calculated and the impact of various inlet concentrations and flow speeds on the separation efficiency as well as the effect of a reflector screen on separation efficiency and particle residence time were discussed. The calculation results indicate that the separator as a whole assumes a double-layer flow structure and features a relatively good symmetry. In general, the radial speed is lower than the axial and tangential speed with an extremely low flow speed within the reflector screen. There exists a short-circuit flow at the inlet of exhaust pipes. This kind of separators provides a low separation efficiency for small particles with a diameter less than 4 μm. The flow speed has a relatively high impact on separation efficiency. The reflector screen can make small particles stagnate in the separator for a longer time, thus enhancing their chances of being separated out. **Key words**: diffusion type cyclone separator, two-phase flow, particle separation, numerical simulation

液柱冲击塔雾化特性的试验研究＝**Experimental Study of the Atomization Characteristics of a Liquid-column Impingement Tower**[刊, 汉] /WANG Jun, GAO Xiang, GUO Rui-tang, et al (State Key Laboratory on the Clean Utilization of Energy Resources under the Zhejiang University, Hangzhou, Zhejiang, China, Post Code: 310027)// Journal of Engineering for Thermal Energy & Power. — 2006, 21(3). —275～278, 282

The atomization effectiveness of a liquid column in a liquid-column impingement tower has a direct influence on the desulfurization efficiency of a whole system. The main influencing factors include: the type of damper plates, liquid inlet flow rate, gas velocity and the clearance between the nozzles and damper plates. On a simulation test rig of a small-sized liquid-column impingement tower, by using particle image velocimetry (PIV) measuring technology, measurements were taken of the gas-liquid two-phase flow field formed by the liquid column atomization inside a simulation test tower. The test results show that the above-mentioned structural factors and operational parameters have a significant effect on the size of liquid droplets in the atomization flow field and their kinematic speed. Moreover, it was found that the liquid droplet size in the flow field complies with Rosin-Rammler distribution law. **Key words**: PIV (Particle Image Velocimetry) technology, liquid-column impingement tower, particle size distribution

高热流密度下 R113 核态沸腾中汽化核心密度的识别＝**Identification of Densities at the Nucleation Sites in a**

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