

微小流量喷嘴雾化特性实验方法

曾青华¹ 孔文俊¹ 范慧杰² 隋春杰¹

(1. 中国科学院工程热物理研究所, 中国科学院轻型动力重点实验室 北京 100190;

2. 中国科学院沈阳自动化研究所 机器人学国家重点实验室 辽宁 沈阳 110016)

摘 要 针对在准确测量微小流量喷嘴雾化特性方面存在的困难, 建立了一套喷雾实验系统和测量研究方法。采用容积法测量喷嘴流量特性, 利用主动轮廓算法(Active Contour Model: ACM) 捕捉喷雾边界, 提取雾化锥角。另外结合激光粒度仪完成了雾滴尺寸及其分布特性的实验研究。容积法克服了因流量小引起的测量误差, 且测量成本低。ACM 方法从原理上保证了提取边界结果的唯一性和最佳可信度, 消除了阈值法, 尤其是直接量取法所包含的主观因素, 提高了实验结果的准确度。

关 键 词: 实验方法; 实验数据; 雾化特性; 主动轮廓算法; 微小流量喷嘴

中图分类号: TK16 文献标识码: A

引 言

喷嘴在航空发动机、燃气轮机、火箭发动机、锅炉等动力设备中均得到广泛应用。喷嘴良好的雾化特性可以改善点火性能、提高火焰的稳定性及燃烧效率。

微小流量喷嘴大量应用在贫油直喷(Lean Direct Injection: LDI) 燃烧室中。LDI 燃烧室^[1~6]是一种新型低污染燃气轮机燃烧室。多个这种微小流量喷嘴耦合结构尺寸极小的空气旋流器作为低污染燃烧单元被安装在 LDI 燃烧室的头部。相比传统燃烧室, 微小流量喷嘴的喷雾特性更大程度影响到火焰的稳定及污染物的排放。由于流量极小, 很难找到合适流量计准确测量该喷嘴的流量特性。另外, 流量小导致雾锥内液雾浓度极低, 此时液雾边界很难分辨, 若继续采用传统处理方法如直接量取法、阈值法测量雾化锥角^[7~11], 由于这些方法带有很强的主观性, 导致测量结果会出现很大误差。

针对在准确测量微小流量喷嘴雾化特性方面存在的上述困难, 建立一套喷雾实验系统并提出测量方法。采用容积法测量喷嘴流量特性, 利用主动轮廓算法(Active Contour Model: ACM) 捕捉喷雾边界,

提取雾化锥角。另外, 结合激光粒度仪完成雾滴尺寸及其分布特性的实验。为微小流量喷嘴雾化性能的测量提供了研究方法。

1 喷雾实验系统

喷雾实验系统包括供油系统, 喷雾图像采集系统, 马尔文粒径测量系统等, 如图 1 所示。供油系统包括进油和回油系统, 考虑到微小流量喷嘴喷口极小, 为防止堵塞, 油路中设置了三级滤油器。滤芯采用的是 800 目的筛网, 可以过滤掉粒径大于 18 μm 的杂质。另外, 连接了高压气源, 在喷嘴堵塞后及使用后可以进行吹扫。供油压力由压力变送器测量, 精度等级为 0.5。喷雾图像采集由有效像素为 500 万的数码相机完成。雾滴尺寸及其分布特性由 LSA - III 型激光粒度仪实现。

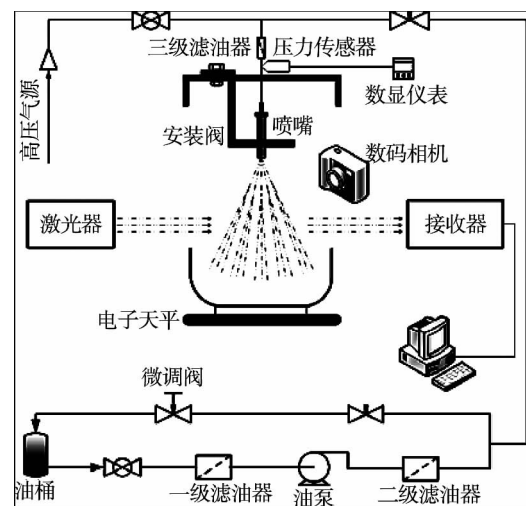


图 1 喷雾实验系统

Fig. 1 Spray test system

实验喷嘴为商用微小流量喷嘴。该喷嘴标称参数为: 压力 1 MPa, 流量 1.15 kg/h, 雾化锥角 60°。

收稿日期: 2012 - 12 - 28; 修订日期: 2013 - 02 - 21

基金项目: 国家自然科学基金资助项目(50936005, 50876110), 国家高技术研究发展(863) 计划基金资助项目(2007AA050501)

作者简介: 曾青华(1982 -), 男, 湖南常宁人, 中国科学院大学博士研究生; 第 3、4 作者均就读于中国科学院大学博士研究生。

通过实验获得不同压力下的该喷嘴的雾化特性。

2 实验及数据处理方法

2.1 流量实验方法

由于流量极小,因而难以采用普通流量计直接准确测量,虽然在国外可以找到这种小量程的流量计,但价格却极其昂贵。为了低成本高精度获得喷嘴的流量特性,本研究采用容积法进行测量。实验时,对于每次不同压力下的稳态喷雾,用容器收集液雾,用精度为 0.1 g 的电子天平采集质量,并同时用秒表计量液雾收集的时间。为了减少液雾收集开始与结束时产生的误差,实验前进行了样本采集时间无关性验证。验证发现,样本采集时间分别为 3 min 和 6 min,样本质量误差小于 1%。因此在实验过程中样本采集时间选择为 3 min。根据质量、采集时间就可获得喷嘴的质量流量。

2.2 雾化锥角提取方法

根据喷雾图像,采用 ACM 提取雾化锥角。ACM 是实现区域分割和提取边界的最新方法^[12-13],基本原理是图像中的初始边界曲线在虚拟力的推动下演化,最终按照虚拟能量最小的原则自动停留在目标边界上^[14]。目标边界由偏微分方程描述,通过数值求解最终予以确定。该方法从原理上保证了提取边界结果的唯一性和最佳可信度,避免了阈值法尤其是直接量取法所包含的主观因素。

图 2 以一个算例给出了 ACM 提取雾化锥角的演化过程。图 2 中的横坐标和纵坐标均表示为像素。图 2(a) 为本次采集到的一副典型的喷雾图像;图 2(b-d) 是采用 ACM 方法提取喷雾边界的演化过程。从图中看出,初始捕捉到的液雾边界经过不断演化,逐渐向真实的雾锥边界转换,最后演化停止得到雾锥边界。由于最终目标边界是依据虚拟能量最小的原则由偏微分方程的解来确定,因此 ACM 依据图像自动得出的边界是最佳选择,不受人为因素的影响,且结果具有最佳可信度。从图 2(d) 看出,ACM 不仅能够清晰地捕捉到雾锥边界,同时喷雾矩在离喷口一定距离位置处出现的收缩特征也被成功捕捉到。求解过程中,相邻两次迭代间雾化锥角的误差小于 0.1%,认为计算收敛,从而最终确定喷嘴雾化锥角。

2.3 雾滴尺寸及其分布特性实验方法

雾滴尺寸及其分布特性通过一套 LSA-III 型激光粒度仪实现。该粒度仪的接收器采用焦距 300

mm 的透镜,粒径探测范围为 5 ~ 584 μm。雾滴平均直径用索太尔平均直径(SMD)表征,即:

$$SMD = \frac{\sum n_i d_i^3}{\sum n_i d_i^2} \tag{1}$$

式中: d_i —探测范围内雾滴的直径, μm; n_i —探测范围内直径为 d_i 的雾滴数目。

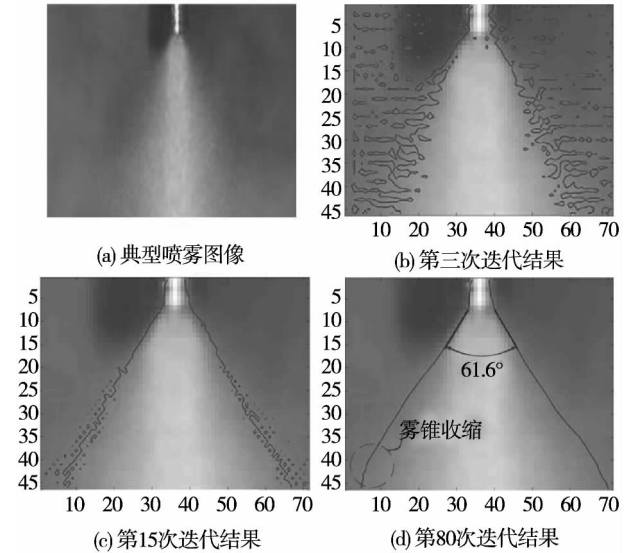


图 2 ACM 提取喷雾边界的演化过程

Fig. 2 Evolution process of the spray boundary extracted by using the ACM

获得的雾滴尺寸分布采用 Rosin - Rammler 模型表征。SMD 及尺寸分布特性通过操作粒度仪的终端处理机可自动获得。

3 实验结果及分析

3.1 流量特性及流量系数

喷嘴流量特性指喷嘴流量随供油压力的变化规律。图 3 为容积法测得的该喷嘴的流量特性。横坐标表示供油压力,单位 MPa,纵坐标表示喷嘴出口流量,单位 kg/h。实验结果表明:喷嘴流量随供油压力增大而增大;开始阶段,流量变化迅速,但随着供油压力的继续增大,流量变化渐趋平缓。对获得的实验数据,采用最小二乘法进行回归分析,可以得到流量与供油压力及喷口直径之间关系式:

$$q_m = 0.4535(\pi d_0^2 / 4) \sqrt{2\Delta p / \rho_0} \tag{2}$$

式中, q_m —质量流量, kg/s; d_0 —喷口直径, m; Δp —供油压力, Pa; ρ_0 —燃油密度, kg/m³。燃油采

用的是 0 号轻柴油,密度由实验测定, $\rho_0 = 837 \text{ kg/m}^3$ 。

理论上,单路压力喷嘴的流量与供油压力及喷口直径间的关联式为:

$$q_m = \mu (\pi d_0^2 / 4) \sqrt{2\Delta p / \rho_0} \quad (3)$$

对比式(2)与式(3)看出,该喷嘴流量系数 $\mu = 0.4535$ 。

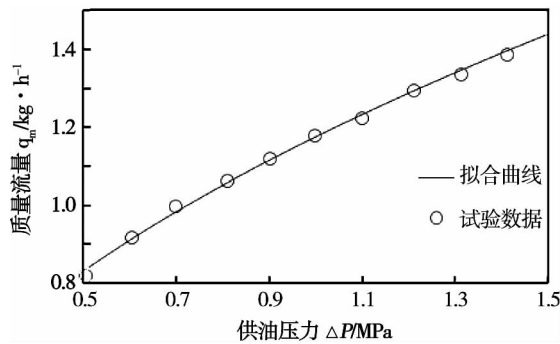


图 3 流量特性曲线

Fig. 3 Flow rate characteristic curves

3.2 雾化锥角

采用 ACM 方法得到了不同供油压力下该型喷嘴的雾化锥角变化情况,横坐标为供油压力,单位 MPa,纵坐标为雾化锥角,单位°,如图 4 所示。供油压力较低时,燃油流速较低,液流受到的离心力较小,受表面张力的影响,喷嘴雾锥未完全打开,雾化锥角较小。随着压力增大,液流受到的离心力增大,液雾向外扩张的惯性力克服表面张力的作用,因而雾化锥角迅速增大。不过,从图上看出,当供油压力超过一定值(约 0.7 MPa)以后,供油压力对雾化锥角的影响很小,此时雾化锥角几乎不变。而这主要是受喷口直径、扩张角等结构参数的制约的缘故。

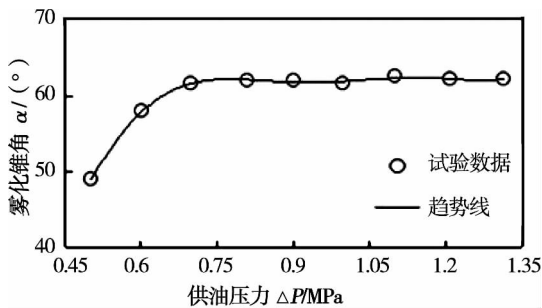


图 4 雾化锥角随供油压力变化情况

Fig. 4 Changes of the atomization cone angle with the oil supply pressure

3.3 SMD 及其分布

实验在喷嘴出口下游 15、25、35、45 和 55 mm 处分别进行了不同供油压力下的 SMD 测量。图中横坐标为供油压力,单位 MPa,纵坐标为 SMD 值,单位 μm 。每种工况下重复进行 5 次,并进行误差分析,确保最终实验数据准确可靠。图 5 给出了实验结果。图中 $z_i (i = 1, 2, 3, 4, 5)$ 表示测量区域中心所在位置, z_i 数值为该位置距喷嘴出口端面的垂直距离。总体来看,随着供油压力增大,喷雾速度不断增加,从而使得雾滴与周围气流间的相对速度变大,以致气流对液膜的作用不断增大,液雾不断破碎,从而导致 SMD 随着供油压力增大呈现减小趋势。不过,受喷嘴结构的影响,供油压力增至一定程度之后,再增大压力对雾滴尺寸的影响逐渐变小,因此 SMD 的变化率表现为开始阶段, SMD 变化迅速,后期 SMD 变化渐趋平缓。要想获得更小粒径的雾滴,需要更换喷嘴型号。

另外,喷雾平均粒径沿喷雾轴向的变化呈现一定规律。距离喷口越远, SMD 越大。喷嘴下游 SMD 增大,是由于雾滴相互碰撞的几率增大,更容易发生雾滴的聚合。

从图 5 还可看出,该小流量油嘴的雾化破碎区很短,即在距喷口很短的距离内即完成了雾滴的基本雾化。如图 $Z = 15 \text{ mm}$ 处, SMD 很小,且随供油压力的变化符合上述规律,说明该位置即已处于雾化完成区了。

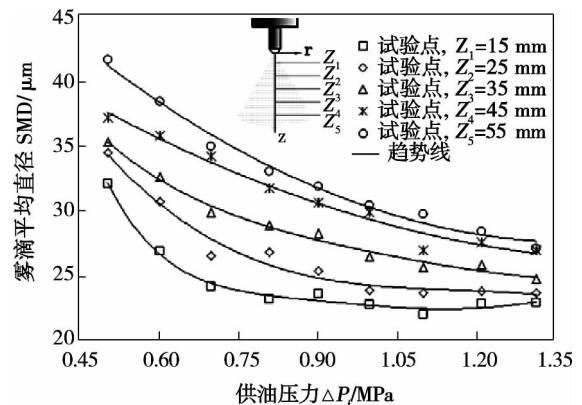


图 5 SMD 随供油压力变化情况

Fig. 5 Changes of the SMD with the oil supply pressure

4 结 论

本研究针对在准确测量微小流量喷嘴雾化特性方面存在的困难,建立了一套喷雾实验系统并提出测量研究方法。采用容积法测量喷嘴流量特性,利用 ACM 方法捕捉喷雾边界,提取雾化锥角,结合激光粒度仪完成雾滴尺寸及其分布特性的研究。实验获得了微小流量喷嘴的流量、雾化锥角以及索太尔直径分布等雾化特性,为微小流量喷嘴雾化特性的测量提供了一套切实可行的实验研究方法。

参考文献:

[1] Iannetti A ,Tacina R ,Cai J ,et al. Mult-swirler aerodynamics: CFD predictions [R]. AIAA - 2001 - 3575 2001.

[2] Tacina R ,Wey C ,Laing P ,et al. A low NOx lean-direct injection , multipoint integrated module combustor concept for advanced aircraft gas turbines [R]. NASA/TM - 2002 - 211347.

[3] Yang S L ,Siow Y K ,Peschke B D ,et al. Numerical study of nonreacting gas turbine combustor swirl flow using Reynolds stress model [J]. Journal of Engineering for Gas Turbines and Power 2003 ,125 (3) : 804 - 811.

[4] Tacina R ,Mao C P ,Wey C. Experimental investigation of a multiplex fuel injector module with discrete jet swirlers for low emission combustors [R]. AIAA - 2004 - 0135 2004.

[5] Fu Y ,Jeng S M ,Tacina R. Characteristics of the swirling flow in a multipoint LDI combustor [R]. AIAA 2007 - 846 2007.

[6] Dewanji D ,Rao A G ,Pourquie M ,et al. Investigation of flow characteristics in lean direct injection combustors [J]. Journal of Propulsion and Power 2012 ,28 (1) : 181 - 196.

[7] 刘定平 ,余海龙. 基于“液包气”雾化的脱硫喷嘴特性实验 [J]. 动力工程学报 2012 ,32 (9) : 693 - 732.

LIU Ding-ping ,YU Hai-long. Experiment of the characteristics of the desulfurization nozzle based on the " gas-in-liquid" atomization [J]. Journal of Power Engineering 2012 ,32 (9) : 693 - 732.

[8] 方立军 李 斌. 压力式喷嘴雾化性能的试验研究 [J]. 热能动力工程 2010 25 (2) : 202 - 205.

FANG Li-jun ,LI Bin. Experimental study of the atomization performance of a pressure type nozzle [J]. Journal of Engineering for Thermal Energy and Power 2010 25 (2) : 202 - 205.

[9] 赵 娜 余永刚 张 琦 等. 液体推进剂模拟工质在离心喷嘴内流动特性研究 [J]. 工程热物理学报 2011 ,32 (12) : 2168 - 2172.

ZHAO Na ,YU Yong-gang ,ZHANG Qi ,et al. Study of the flow characteristics of the liquid propellant simulation working medium inside a centrifugal nozzle [J]. Journal of Engineering Thermophysics 2011 ,32 (12) : 2168 - 2172.

[10] 邓 巍 丁为民 柳平增 等. 基于 MATLAB 的雾化图像处理及雾化角的测定 [J]. 西北农林科技大学学报(自然科学版) , 2006 34 (7) : 155 - 159.

DENG Wei ,DING Wei-min ,LIU Ping-zeng ,et al. Atomization image processing based on the Matlab and determination of the atomization angle [J]. Journal of Northwest University of Science and Technology in Agriculture and Forestry. (Natural Science Edition) 2006 34 (7) : 155 - 159.

[11] 金仁喜 袁江涛 杨 立 等. 压力喷嘴常温下雾化特性实验研究 [J]. 海军工程大学学报 2012 24 (3) : 52 - 56.

JIN Ren-xi ,YUAN Jiang-tao ,YANG Li ,et al. Experimental study of the atomization characteristics of a pressure nozzle at the normal temperature [J]. Journal of University of Naval Engineering , 2006 24 (3) : 52 - 56.

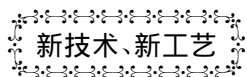
[12] Kass M ,Witkin A ,Terzopoulos D. Snakes: Active contour models [J]. International Journal of Computer Vision ,1987 ,1 (4) : 321 - 331.

[13] Chan T F ,Vese L A. Active contours without edges [J]. IEEE Transactions on Image Processing 2001 ,10 (2) : 266 - 277.

[14] 王 岳 唐延东 张哲巅 等. 利用主动轮廓算法提取火焰前鋒 [J]. 燃烧科学与技术 2005 ,11 (6) : 543 - 546.

WANG Yue ,TANG Yan-dong ,ZHANG Zhe-dian ,et al. Extraction of the leading edge of the flame by using the active contour algorithm [J]. Combustion Science and Technology ,2005 ,11 (6) : 543 - 546.

(丛 敏 编辑)



中国石油公司订购 6 台 RB211 压缩机组

据《Gas Turbine World》2013 年 3 - 4 月刊报道,中国石油公司向 Rolls - Royce 公司订购 6 台 34 MW RB211 驱动的管线压缩机组和签定有关服务的合同。

这些压缩机组将用于西气东输管线项目的 3 号管线,西气东输管线是世界上最长的天然气管线。至此,在中国和中亚天然气管线上安装的 RB211 机组的总数达到 56 台。

在 2015 年完成时,该 7 000 km 长的西气东输 3 号管线将使天然气输送从中国西部的新疆自治区连接到在东南部的福建省,每年将输送最多到 300 亿 m³ 天然气。

(吉桂明 摘译)

merical simulation ones that their Mach number distributions on the pressure surface are in relatively good agreement and the test value on the suction surface is slightly higher than the calculated ones. The relative position between the front and rear row cascade blades has a most important influence on the tandem cascade and it deserves an in-depth investigation. **Key words:** tandem cascade ,flow field characteristics ,numerical simulation ,oil flow display

基于激光扫描的轴流压缩机叶片反求技术探讨 = **Exploratory Study of the Reverse Solution-seeking Technology for Axial Flow Compressor Blades Based on the Laser Scanning** [刊 ,汉] SONG Wei ,LAI Xi-de ,LI Guang-fu ,et al(College of Energy Source and Environment ,West China University ,Chengdu ,China ,Post Code: 610039) //Journal of Engineering for Thermal Energy & Power. -2013 ,28(5) . -455 ~460

To solve the problems relating to numerical models for blade modification design ,aerodynamic optimization and repairing based on a real object in actual engineering projects during operation of an axial flow compressor ,the portable type laser scanning technology was used to develop a high precision and efficiency flow path for reverse design of axial flow compressor blades. In compliance with the geometrical characteristics of and aerodynamic optimization design requirements for axial flow compressor blades ,the laser triangular method was adopted with auxiliary planes and marking points being added to the blade leading edges ,trailing edges and tips ,enhancing the point cloud data acquisition efficiency of the blade. In the light of the problem that the curved surface in the blade body zone had a low fitting precision and the curved surface pieces around the tenon area were of self-intersection ,an interactive method for dividing the curved surface pieces of the blade based on the flow streamlines ,meridian lines ,contour lines and their extension lines was proposed to express the tenon end surface area of non-four-edges but N-edges by using several curved surface pieces of four edges according to the flow path "detect the contour and its extension lines-subdivide and extend the contour lines-structure the curved surface pieces-repair them" with the method for man-machine interactively adding auxiliary contour lines being employed and obtain a model for the curved surface meeting the requirements for engineering projects. A high efficiency reverse solution-seeking technology for axial flow compressor blades was studied and developed ,including point cloud data acquisition ,processing ,curved surface restructuring and precision evaluation of a blade. The technology in question can be applied in an actual engineering project when repairing a large-sized axial flow compressor. **Key words:** axial flow compressor blade ,reverse solution-seeking technology ,point cloud data acquisition ,curved surface restructuring

微小流量喷嘴雾化特性实验方法 = **Method for Testing the Atomization Characteristics of a Micro Flow**

Nozzle [刊, 汉] ZENG Qing-hua, KONG Wen-jun, SUI Chun-jie (Chinese Academy of Sciences Key Laboratory on Light-duty Type Power Devices, Engineering Thermophysics Research Institute, Chinese Academy of Sciences, Beijing, China, Post Code: 100190), FAN Hui-jie (National Key Laboratory on Robotics, Shenyang Automation Research Institute, Chinese Academy of Sciences, Shenyang, China, Post Code: 110016) // Journal of Engineering for Thermal Energy & Power. - 2013, 28(5). - 461 ~ 464

In the light of the difficulty existing in accurately measuring the atomization characteristics of a micro flow nozzle, established were an atomization system and a method for studying the measurement. The volumetric method was used to measure the flow characteristics of the nozzle and the active contour model(ACM) was utilized to capture the atomization boundary and figure out the atomization cone angle. Furthermore, by using a laser particle size analyzer, an experimental study of the sizes and distribution characteristics of the atomized droplets was completed. The volumetric method can overcome the measurement error caused by a small flow rate and lead to a low measurement cost. The ACM method can theoretically guarantee the uniqueness of the atomization boundary captured and optimum credibility, eliminating the objective factors involved in the threshold value method, especially the direct measurement method, thus enhancing the accuracy of the test results. **Key words:** test method, test data, atomization characteristics, active contour algorithm, micro flow nozzle

低温余热蒸汽 ORC 发电系统热力性能实验研究 = **Experimental Study of the Thermal Performance of a Low Temperature Waste Heat Steam ORC Power Generation System** [刊, 汉] YANG Xin-le, HUANG Fei-fei (College of Mechanical Engineering, Liaoning Engineering Technology University, Fuxin, China, Post Code: 123000), ZHAO Yang-sheng, FENG Zeng-chao (Mining Process Research Institute, Taiyuan University of Science and Technology, Taiyuan, China, Post Code: 030024) // Journal of Engineering for Thermal Energy & Power. - 2013, 28(5). - 465 ~ 470

To obtain the thermal performance of a low temperature waste heat power generation system and its influencing factors, set up was a low temperature waste heat steam ORC thermal power generation test system. With a 5 kW back pressure steam turbine serving as the driving machine, R11 working medium was used to perform the ORC thermal performance testing experiment. The test results show that under a 110 °C heat source, when the steam pressure has exceeded 0.85 MPa, the working medium exists in gas-liquid two phase state and when the temperature of the heat source has increased to 120 °C, the working medium is in its superheated state. To rise the temperature of the heat source can increase the allowable evaporation pressure of the working medium admitted by the steam turbine and the