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# 弯尾管亥姆霍茨型无阀自激脉动燃烧器传热特性

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摘 要: 在传统的亥姆霍茨型脉动燃烧器基础上,取消了机械阀,采用连续供气方式,建立了弯尾管亥姆霍茨型无阀自激脉动燃烧器实验系统,设计了0°、45°,90°和135°弯尾管结构形式,实验研究了弯尾管亥姆霍茨型无阀自激脉动燃烧器尾管的传热特性。结果表明: 在相同频率下脉动燃烧器传热系数随压力振幅的增大而增大,脉动流的传热系数约为相同雷诺数下稳态流传热系数的2.4-4.6倍; 在相同压力振幅下脉动燃烧器传热系数随脉动频率的增大而增大,脉动流传热系数约是相同雷诺数下稳态流传热系数的3.3-4.7倍。

关 键 词: Helmholtz型脉动燃烧器; 无阀自激式; 弯尾管; 传热特性; 压力振幅; 频率
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## 引 言

脉动燃烧能产生强大的烟气冲力,燃烧效率高、传热系数大、污染物排放量低、具有自吸增压功能[1-3]。脉动燃烧器的最大优点之一是尾管的传热系数比一般燃烧器的传热系数大,其原因主要是脉动燃烧器尾管中的烟气流脉动振荡[4-5]。

脉动燃烧器的换热系数比处于同样雷诺数下的稳定流动换热系数高很多。亥姆霍茨型脉冲燃烧器尾管传热系数是一般燃烧器的2倍多[6-7],传热系数随燃烧室压力振幅和频率的增大而增大; 文献[8]实验测试得到换热系数受脉动频率和紊流度的影响,脉动流场 $Nu$ 数约为稳定流场 $Nu$ 数的2倍。文献[9-10]建立相应的数学模型,给出了尾管传热准则方程。

上述研究主要是针对机械阀脉动燃烧器进行的,且主要考虑直尾管的传热特性。本研究建立了弯尾管Helmholtz型无阀自激脉动燃烧器实验系统,取消了传统的机械阀,采用连续供气方式,利用燃烧器声学结构与燃料燃烧放热耦合实现脉动燃烧,可以自主调节热负荷,大大提高了燃烧器的运行可靠性和稳定性,设计了不同的弯尾管结构形式,可任意布置受热面,调节去耦室内的相对压力,能够改变脉动燃烧器的运行特性,该脉动燃烧器可实现其设备的大型化。针对所建立的弯尾管亥姆霍茨型无阀自激脉动燃烧器的尾管传热特性进行了实验研究,得到脉动振幅和频率对尾管传热的影响。

## 1 实验装置

### 1.1 燃烧器结构

本研究设计的脉动燃烧器主要是由混合室、燃烧室、弯尾管、去耦室及排烟管组成,所有组件由法兰连接,结构尺寸如图1所示,这种结构与传统的亥姆霍茨型脉动燃烧器结构相似,但取消了机械单向阀门,采用连续进气的方式供气。

混合室一端封闭,另一端与燃烧室相通,距离混合室封闭端50 mm处沿周向开4个进气口,燃气和空气进气口各2个,燃气进气口和空气进气口的轴线成90°角,使燃气和空气射流互击混合。尾管相当于亥姆霍茨谐振管,与燃烧室共同组成谐振系统,是燃烧器的主要换热面。尾管的截面尺寸为 $\varphi 32\ mm \times 3$ mm,尾管有4种不同规格,弯曲角度分别为0°、45°、90°和135°,其展开长度为1 500 mm,弯曲半径为 $R$150 mm,弯曲位置在尾管中部。尾管外设置由铸铁加工的水套,尺寸为 $\varphi 60\ mm \times 2$ mm,长1 200 mm,水套内的冷却水对尾管进行冷却。冷却水由尾管出口处的水套底部流入,由尾管入口处的水套顶部流出,冷却水充满整个水套,使尾管内的热烟气与水套内的冷水形成逆流换热。

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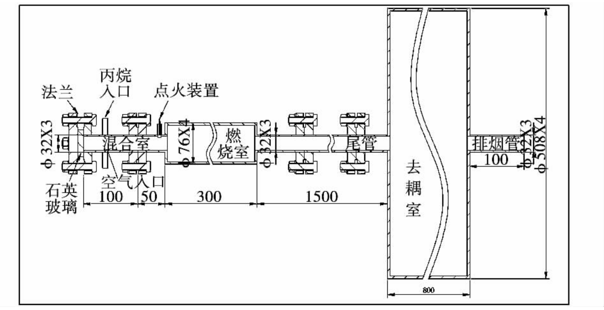


图 1　脉动燃烧器基本结构及尺寸(mm)

Fig. 1 Basic structure and dimensions of a pulsation burner(mm)

### 1.2　测量方法

实验中使用的测量仪器包括转子流量计、热电偶、压力传感器和烟气分析仪。转子流量计用来测量丙烷和空气的流量，量程分别为 0 – 0.6 $m^3/h$ 和 0 – 20 $m^3/h$。图 2 为 90°弯尾管脉动燃烧器实验装置温度测点布置图，其中测点 1 – 测点 8 的温度采用 S 型热电偶测量，量程为 0 – 1 600 ℃；测点 9(去耦室中心温度)及水套内冷却水的进出口温度采用 JM222U 型便携式数字温度计测量，量程为 – 50 – 199.9 ℃。脉动燃烧器温度场高频振荡，瞬时温度的变化频率在 40 Hz 左右，而本实验中热电偶的响应时间远不能满足温度的瞬态变化时间，故测得的温度值为测点在一段时间内的平均温度。扩散硅压阻式传感器(PCM300)用来测量燃烧室及尾管压力，并根据所测数值确定燃烧器频率。烟气分析仪用于测量尾管出口烟气的成分。实验中温度和压力的数据由工控机采集卡(PCL – 818LS)实时采集，采集频率最高可达 40 kHz，远远高于燃烧器的运行频率。

## 2　实验结果及分析

高温烟气流经尾管受热面时，除有对流换热外，还有辐射换热。通过计算大量实验工况，得到其辐射传热份额占对流传热份额均小于 6%，因此在传热实验数据处理和传热数值模拟时都忽略了辐射传热的影响[12]。稳态流动时尾管中对流传热系数计算过程为：首先确定尾管烟气平均流速，再确定稳定流 $Nu$，最后确定稳态流传热系数；脉动流尾管传热系数的计算过程为：首先确定尾管总的传热系数，然后确定冷却水侧传热系数，最后确定烟气侧传热系数；具体计算过程及方法参考文献[11]。

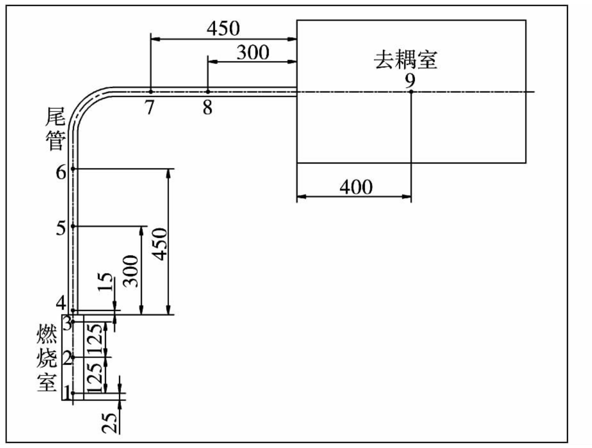


图 2　90°弯尾管脉动燃烧器温度测点布置(mm)

Fig. 2 Arrangement of the temperature measuring points in the 90° tail bend of a pulsation burner(mm)

在不改变燃烧器结构的情况下，通过改变供气压力和过量空气系数得到不同燃烧室脉动压力振幅和频率，通过大量的实验测试，得到相同或相近频率(燃烧室压力振幅)下对流换热系数随燃烧室压力振幅(频率)的变化关系。

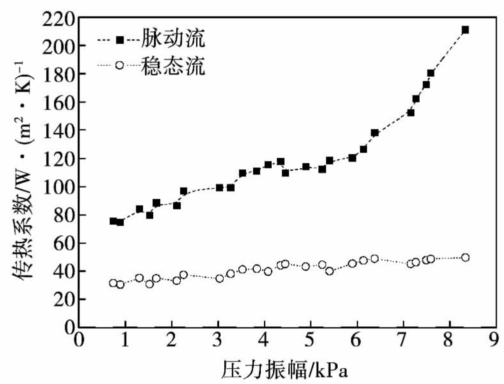


图 3　直尾管传热系数随压力振幅的变化($f \approx 49$ Hz)

Fig. 3 Changes of the heat transfer coefficient of the straight tail tube with the pressure amplitude($f \approx 49$ Hz)

### 2.1　压力振幅对传热的影响

图 3 是直尾管脉动燃烧器在频率约为 49 Hz 下传热系数随压力振幅的变化。由图可知，在相同频率下直尾管传热系数随压力振幅的增大而增大，脉

动流的传热系数约为相同雷诺数下稳态流传热系数的 2.4－4.5 倍。脉动振幅的增加导致热烟气在尾管内的扰动增强，有效破坏了边界层，使热边界层的厚度减薄，进而增强了换热。

图 4－图 6 分别是 45°、90°和 135°弯尾管在一定频率值下传热系数随燃烧室压力振幅的变化。在相同频率下弯尾管传热系数随压力振幅的增大而增大，脉动流传热系数约为相同雷诺数下稳态流传热系数的 2.4－4.6 倍，其变化规律与直尾管相同。

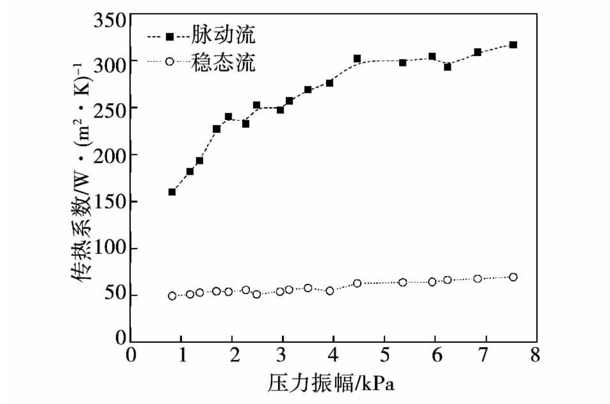


图 4　45°弯尾管传热系数随压力振幅的变化( $f \approx 46$ Hz )

Fig. 4 Changes of the heat transfer coefficient of the tail bent tube at 45° with the pressure amplitude ( $f \approx 46$ Hz )

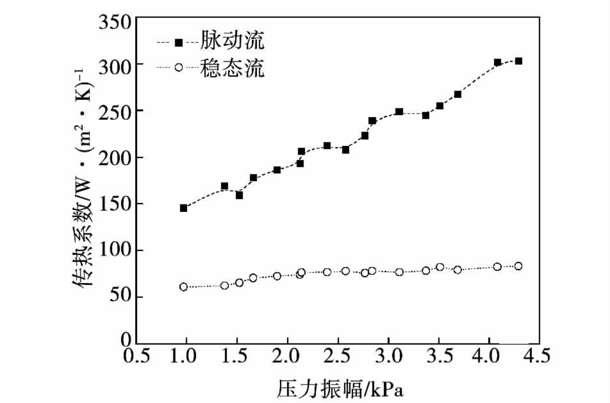


图 5　90°弯尾管传热系数随压力振幅的变化( $f \approx 26$ Hz )

Fig. 5 Changes of the heat transfer coefficient of the tail bent tube at 90° with the pressure amplitude ( $f \approx 26$ Hz )

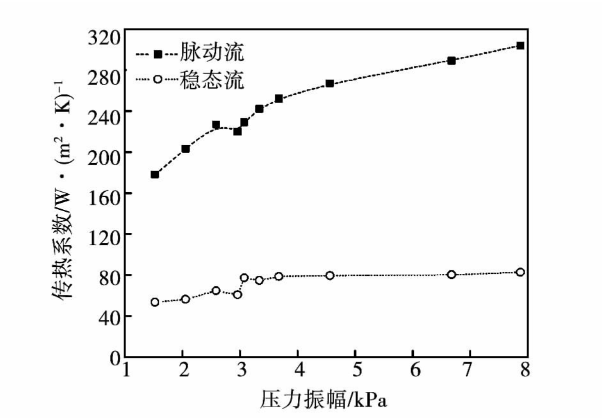


图 6　135°弯尾管传热系数随压力振幅的变化( $f \approx 25$ Hz )

Fig. 6 Changes of the heat transfer coefficient of the tail bent tube at 135° with the pressure amplitude ( $f \approx 25$ Hz )

## 2.2　脉动频率对传热的影响

图 7 是直尾管脉动燃烧器在压力振幅约为 4 560 Pa 时传热系数随脉动频率的变化，在相同压力振幅下直尾管传热系数随脉动频率的增大而增大。在实验工况条件下，脉动流传热系数约是相同雷诺数下稳态流传热系数的 3.3－3.5 倍。脉动频率的增大意味着烟气气流扰动增强，进而增强对边界层的扰动，使传热增强。

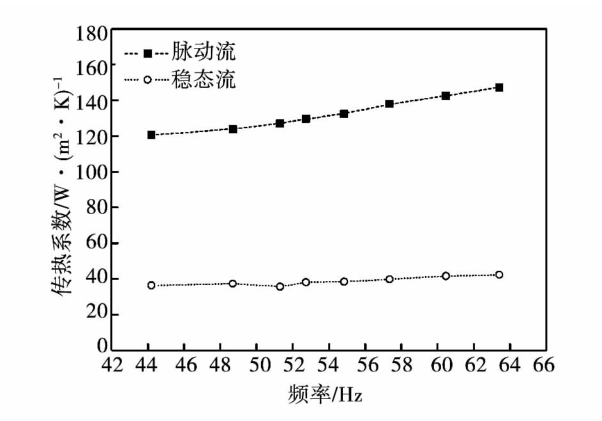


图 7　直尾管传热系数随频率的变化（压力振幅约为 4 560 Pa）

Fig. 7 Changes of the heat transfer coefficient of the straight tail tube with its frequency ( pressure amplitude is around 4 560 Pa)

图 8 - 图 10 分别是 45°、90°和 135°弯尾管在一定压力振幅下传热系数随脉动频率的变化，在相同压力振幅下弯尾管传热系数随脉动频率的增大而增大，脉动流传热系数约是相同雷诺数下稳态流传热系数的 3.5 - 4.7 倍之间，其变化规律与直尾管相同。

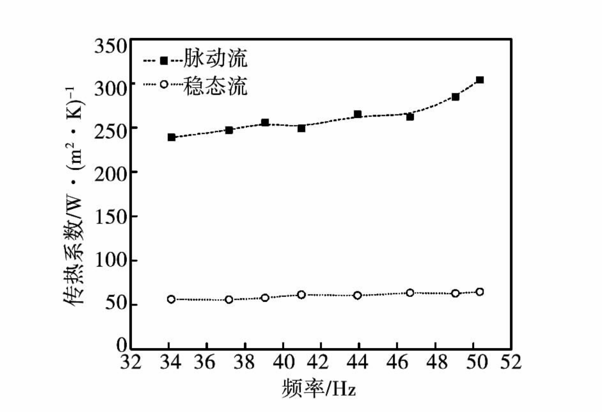


**图 8　45°弯尾管传热系数随频率的变化（压力振幅约为 4 350 Pa）**

Fig. 8 Changes of the heat transfer coefficient of the tail bent tube at 45° with its frequency (pressure amplitude is around 4 350 Pa)

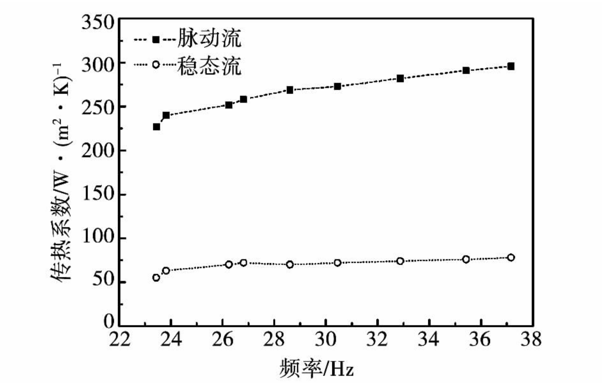


**图 9　90°弯尾管传热系数随频率的变化（压力振幅约为 2 200 Pa）**

Fig. 9 Changes of the heat transfer coefficient of the tail bent tube at 90° with its frequency (pressure amplitude is around 2 200 Pa)

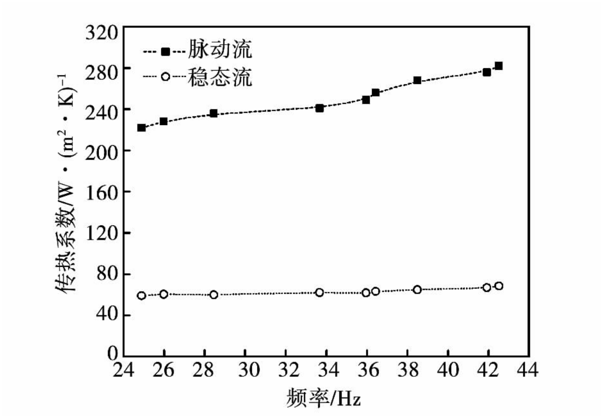


**图 10　135°弯尾管传热系数随频率的变化（压力振幅约为 3 060 Pa）**

Fig. 10 Changes of the heat transfer coefficient of the tail bent tube at 135° with its frequency (pressure amplitude is around 3 060 Pa)

## 3　结　论

对弯尾管（0°、45°，90°和 135°）Helmhotlz 型无阀自激脉动燃烧器传热特性进行了实验研究，得出以下结论：

（1）在相同频率下弯尾管脉动燃烧器传热系数随压力振幅的增大而增大，脉动流的传热系数约为相同雷诺数下稳态流传热系数的 2.4 - 4.6 倍。

（2）在相同压力振幅下弯尾管脉动燃烧器传热系数随脉动频率的增大而增大，脉动流传热系数约是相同雷诺数下稳态流传热系数的 3.3 - 4.7 倍。

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（姜雪梅　编辑）

新技术、新工艺

# GE 9FB 燃气轮机装置的热力试验

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据《Теплоэнергетика》2013 年 9 月刊报道，在“Энел ОГК－5”无限股份公司的中乌拉尔国营地区发电站，ПГУ－410 发电机组于 2011 年 7 月投入运行。

ПГУ－410 蒸燃联合装置的主要设备包括 1 台美国 GE 能源电站系统公司的 MS9001FB 型燃气轮机装置、1 台美国 Nooter/Ericsen 公司的余热锅炉和 1 台 Skoda 公司的蒸汽再热 KT－140－13.3 型双缸冷凝式－热电抽汽式汽轮机。

在 2011－2012 年，全俄热工研究所的专家在不同的外部条件下并在大负荷范围内进行了该机组的热力试验。

列出并分析了 MS9001FB 燃气轮机装置热力试验的结果。根据得到的试验数据，确定了燃气轮机装置及其部件（压气机和涡轮）的实际指标并绘制了特性曲线。

在标准大气条件下，燃气轮机装置的功率为 287 MW，效率为 38.3%。涡轮前燃气温度为 1 315 ℃，涡轮后排气温度为 648 ℃。

（吉桂明　摘译）

signed a control system. Finally, the method above-mentioned was used in a 600 MW supercritical once-through unit. An analysis of the data actually measured proved that the control system can accomplish a stable control over the intermediate point temperature and real-time responded the change of the load at the same time of accommodating to the off-design operating conditions, thus, guaranteeing a safe and economic operation of the electric power system. **Key Words:** nonlinear control, supercritical once-through boiler, intermediate point temperature, load demand

**中心供风气体扩散燃烧特性的数值模拟 = Numerical Simulation of the Air Diffusion Combustion Characteristics of a Central Air Supply Firing Device** 刊,汉 ZHANG Liang, LIU Ming-zhu, HE Zhao-bin (CSIC Harbin No. 703 Research Institute, Harbin, China, Post Code: 150078) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -703-709

By using the numerical simulation method, studied were the air diffusion combustion characteristics of a central air supply flue duct type firing device in a heat recovery steam generator. Under the operating condition of a fuel gas flow rate being 20 $m^3/h$, a contrast of the numerical simulation results of the axial temperature distribution and $NO_x$ concentration distribution at the outlet with the test ones shows that they are in good agreement and proves that the calculation model is correct. The further calculation results indicate that with an increase of the excess air coefficient and the oxygen content of air or a decrease in air temperature, the maximum speed of the gas in the main stream will increase, however, the maximum speed area, speed attenuation characteristics of the main stream and the axial and radial distribution of $CH_4$ component will change not big. When the air excess coefficient is low, the oxygen content is high and the air temperature is high, the flame will be of a "slender" type and to this contrary, the flame will be of a "stubby" type. When the air excess coefficient is low, the oxygen content is low and the air temperature is high, the temperature distribution of the flame will be more uniform. To increase the excess air coefficient and decrease the oxygen content and temperature of air can effectively reduce the NOx emissions at the outlet. In addition, the CO concentration is only relevant to the excess air coefficient (i. e. the air flow rate) but irrelevant to the oxygen content and the temperature of air. **Key Words:** central air supply, diffusion combustion, flow characteristics, flame characteristics, emission characteristics

**弯尾管亥姆霍茨型无阀自激脉动燃烧器传热特性 = Heat Transfer Characteristics of a Bent Tail Tube Helmholtz Type Valveless Self-excited Pulsation Burner** 刊,汉 XU Yan-ying (College of Safety Engineering, Shenyang University of Aeronautics and Astronautics, Shenyang, China, Post Code: 110136), ZHAI Ming, DONG Peng (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -610-714

A test system for bent tailpipe Helmholtz type valveless self-excited pulsation burners was set up on the basis of the traditional Helmholtz type pulsation burners with the mechanical valves being removed and a continuous air and fuel supply being adopted. Bent tailpipes including 0°,45°,90° and 135° were designed. The heat transfer characteristics of the pulsation burner were investigated. The research results show that the heat transfer coefficient of the tailpipe increases with an increase of the pressure variation range at a same frequency and the heat transfer coefficient is about 2.4 to 4.6 times higher than that of a steady-state flow at a same Reynolds number. The heat transfer coefficient of the burner increases with an increase of the pulsation frequency in a same pressure variation range, and the heat transfer coefficient is about 3.3 to 4.7 times higher than that of a steady-state flow at a same Reynolds number. **Key Words:** Helmholtz type pulsation burner, no-valve self-excited type, bent tail tube, heat transfer characteristics, pressure amplitude, frequency

1 000 MW **超超临界锅炉水冷壁工质温度计算研究 = Study of the Temperature Calculation of the Working Medium in the Water Walls of a** 1000 **MW Ultra-supercritical Boiler [刊,汉]** TENG Ye, ZHANG Zhong-xiao (College of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200090), ZHANG Zhong-xiao, DONG Jian-cong, LIU Xu-dan (College of Mechanical and Power Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200240) //Journal of Engineering for Thermal Energy & Power. -2014, 29(6). -715-719

With a 1000MW ultra-supercritical tower type boiler serving as the object of study, simplified were the aerodynamic and radiation heat transfer model for furnaces under ultra-supercritical pressures by using a zone division calculation method. The distribution of medium's temperature was calculated under different boiler load conditions. Compared with the measured data, the maximum deviation is 1.66%, indicating that the model can be used to predict the distribution of the working medium temperature. The research results show that the working medium under the supercritical pressure changes directly from the liquid to a vapor state, working medium temperature changes slowly in phase transition zone. There is gas-liquid coexistence zone under subcritical pressure, in which state the working medium temperature remains constant. The saturated water and steam temperature is 362.5 ℃ at the load of 662 MW and 344.8 ℃ at the load of 507 MW. The fluctuation of the working medium temperature is within a range of 2.8 ℃ and the spiral coil tubes exhibit an excellent ability to withstand any disturbance in combustion. The highest steam temperature at the outlet of the water walls is 458.0 ℃. Furthermore, to control the working medium temperature at the outlet of water walls will be favorable to the safety of the water walls. **Key Words:** ultra-supercritical boiler, heat transfer in a furnace, membrane type water wall, working medium temperature

**流动密封阀调节特性实验研究 = Experimental Study of the Regulation Characteristics of a Flow Seal Valve**