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跨临界压力下倾斜下降管内水的传热特性试验研究

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摘 要: 在压力11.5~28 MPa,质量流速450~1 550 kg/(m^2·s),外壁热负荷50~585 kW/m^{2}的工况范围内,对水平倾角为45°的倾斜下降光管内水的传热特性进行了试验研究。实验结果表明:倾斜下降管壁温沿管子周向分布不均匀。在亚临界压力区,倾斜下降管上下母线处的壁温有明显不同,壁温飞升时上下母线的临界干度差值较大。在近临界压力区,倾斜下降管内各母线处的壁温分布相似,壁温飞升时上下母线的干度差值很小。在超临界压力区,传热在拟临界焓值区得到强化,本研究工况下,压力的影响会改变热负荷的作用;在高焓值区,上母线处的壁温会有所降低。根据试验结果,得到了亚临界和近邻界压力区的临界干度关联式和超临界压力水的强制对流传热关联式。

关 键 词: 倾斜下降管;壁温;压力;热负荷

中图分类号: TK124 **文献标识码**: A

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引 言

超临界CFB锅炉是将成熟的CFB锅炉技术与超临界技术进行有机的结合,这类锅炉不仅具有CFB锅炉本身的优点,还具有超临界技术的高效率低煤耗的特点。然而,由于CFB锅炉固有的低炉内热负荷特性,为了降低锅炉高度、改善炉内灰循环和节约成本,超临界CFB锅炉通常会在炉内布置水冷屏受热面[1],以增加蒸发受热面吸热量。在某些情况下,为了弥补一次上升水冷屏的不足,有些锅炉厂商采用类似再热器的U型屏布置方式。这样,在水冷屏管内就存在垂直下降和倾斜下降流动传热过程;另外,由于采用滑压运行方式,水冷屏的运行压力经常在亚临界到超临界的跨临界压力范围内反复变化,为了保证水冷屏管间具有良好的流量分配特性及水冷屏的工作安全,倾斜下降管部分必须要有正常甚至优良的传热特性。所以,有必要对倾斜下降管在跨临界压力范围内的传热特性进行试验研究,以保证其工作在安全范围内。

在公开发表的文献中,对倾斜下降管内的流动传热过程的研究比较少。沈植等以超临界CFB锅炉为应用背景[2],对垂直下降管的流动传热特性开展了试验研究。目前,国内外研究者以水和二氧化碳为工质,对水平管、倾斜管内上升流动和垂直管内上升流动的传热特性进行了大量研究[3-11],而且试验研究多集中在超临界压力范围内,对跨临界压力范围内管内高温高压水的传热特性的研究较少。因此,本研究采用Φ25×2.5 mm、水平倾角为45°的光管,以水为工质,在亚临界压力到超临界压力范围内,深入研究了倾斜下降流动的传热特性。

1 试验系统及试验方法

本试验在西安交通大学动力工程多相流国家重点实验室的高压汽水两相流及传热实验台上进行,试验回路系统如图1所示。试验所用工质为去离子水,采用电加热方式,在预热段和试验段接通低电压、大电流的交流电,依靠管壁自身热阻产生的热量进行全周加热。

试验段为长2 000 mm,材质1Cr18Ni9Ti的光管,倾斜固定,设置10个壁温测量截面,每个截面布置一定数量的热电偶。试验段结构和温度、压力测点布置如图2所示。

工质压力由智能压力变送器测得,试验段压降由智能差压变送器测量。工质流量通过RHM15型质量流量计来测量,由旁路流量调节阀控制。工质温度由安装在预热段和实验段前后的Φ3 mm镍铬-镍硅铠装热电偶测得。试验段外壁温度由Φ0.5 mm镍铬-镍硅热电偶测量。预热段和试验段的电加热功率均由试验中测得的电压电流有效值计算而得。试验数据均由Solarton IMP3595分散式数据采

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集系统自动采集，并输入工程控制机进行处理。

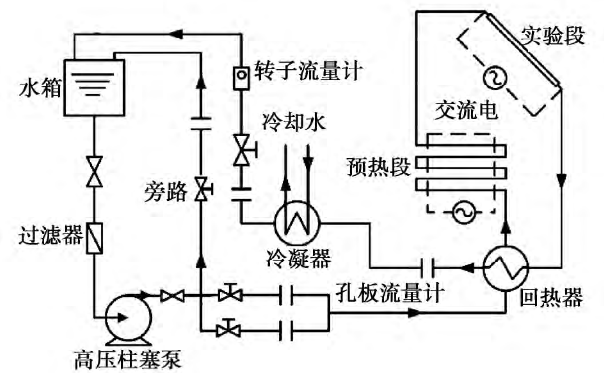

图 1　试验回路系统简图

Fig. 1 Schematic diagram of a test loop system

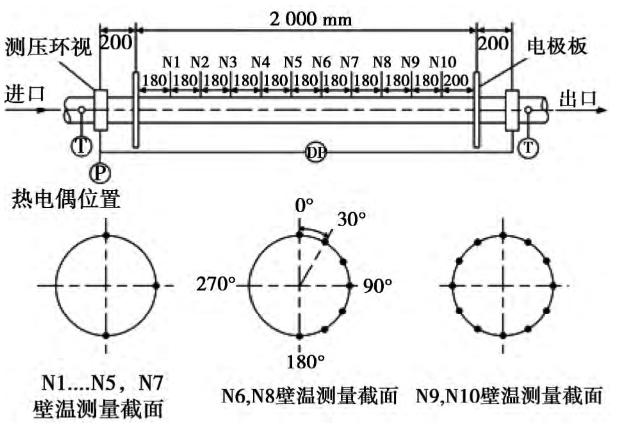

图 2　实验段结构及测点布置

Fig. 2 Structure of the test section and arrangement of the measuring points

试验主要参数：压力 11.5 ~ 28 MPa，质量流速 450 ~ 1 550 kg/(m²·s)，外壁热负荷 50 ~ 585 kW/m²。试验方法：保持试验段的压力、流量及热负荷不变，不断增加预热段功率来提高试验段进口工质焓值，以模拟超临界 CFB 锅炉的运行条件。

2　试验结果及分析

2.1　亚临界压力区传热特性

图 3 表示压力 $p = 12$ MPa，热负荷 $q = 250$ kW/m²，质量流速 $G = 450$ kg/(m²·s) 时，倾斜下降管周向内壁温度随焓值的变化。从图中可以看出，倾斜下降管内壁温度随周向角度的增大而减小，上母线处内壁温度最高，下母线处内壁温度最低。从图中可以观察到两类不同特点的壁温曲线：0° ~ 90°处的壁温曲线具有相同形状和趋势，均出现两次壁温飞升；120° ~ 180°处的壁温曲线则只出现一次壁温飞升。在 0° ~ 90°母线处，发生第一次壁温飞升时的干度不大于 0.16，可认为发生了 DNB(偏离核态沸腾)；第二次壁温飞升的干度值约为 0.6，可认为发生了干涸，而 120° ~ 180°母线处的临界干度为 0.8 左右，表明在亚临界区，倾斜下降管上下母线处临界干度相差较大。

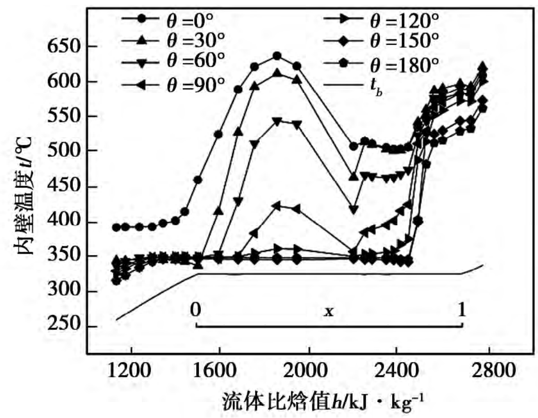

图 3　亚临界压力区倾斜下降管周向内壁温随焓值变化

Fig. 3 Changes of the inner wall temperature of the oblique downcomer with enthalpy in the subcritical pressure zone

图 4 示出了压力 $p = 12$ MPa，质量流速 $G = 450$ kg/(m²·s) 时，热负荷对上下母线 $\theta = 0°$和 $\theta = 180°$处的内壁温度随焓值变化的影响。从图中可以看出，不同热负荷条件下，DNB 和干涸均在上母线处产生，而下母线处仅有干涸产生；热负荷增大，上母线处 DNB 发生提前，下母线处临界干度值减小，壁温峰值显著增大，上下母线处的温差也明显增大，这表明在亚临界区，增大热负荷，不仅削弱管内换热强度，而且会增大倾斜下降管壁温的周向不均匀性。

根据已有结论，一般而言，热负荷越高、质量流速越小的工况，内壁温度越高，但这一规律会受到压力变化的影响。如图 5 所示两个工况，15 MPa 工况的热负荷略高、质量流速略小，在过冷段，15 MPa 工况上下母线处的壁温略高，表明传热主要受到热负荷和质量流速大小的影响，这种情况在干涸后的传热段更加明显；但在两相正常沸腾换热段，壁温分布相反，15 MPa 工况的壁温明显低于 18 MPa 工况。从图中还可以看出，18 MPa 工况上下母线处的临界

干度的差值明显小于 15 MPa 工况，这表明，压力升高，一方面会抑制核态沸腾的强度，这对两相沸腾传热是不利的；另一方面，压力升高减小了倾斜下降管上下母线处换热条件的差异，但这是以削弱下母线处的换热为前提的。

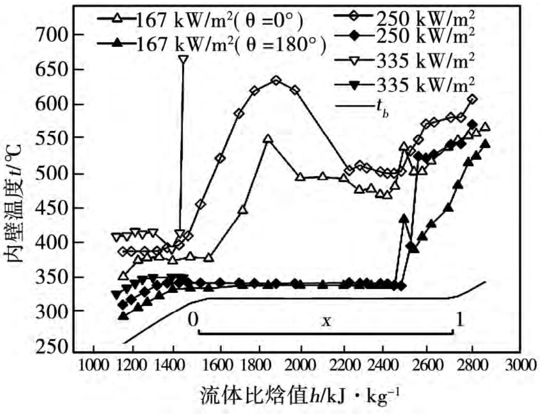

图 4　热负荷对内壁温度的影响

Fig. 4 Effect of the heat load on the inner wall temperature

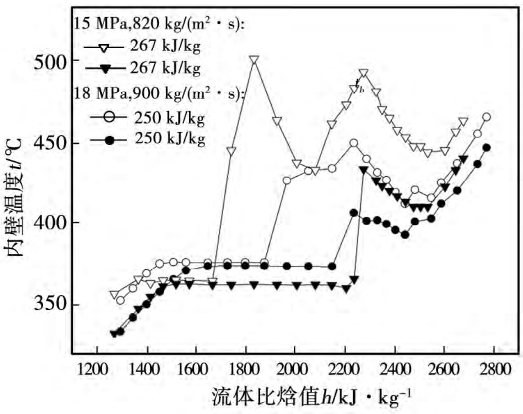

图 5　亚临界压力区压力对上下母线壁温随热负荷变化的影响

ig. 5 Effect of the pressure in the subcritical pressure zone on changes of the wall temperature on the top and bottom surface with the heat load

2.2　近临界压力区传热特性

图 6 示出了压力 $p = 20.5$ MPa，热负荷 $q = 418$ kW/m^2，质量流速 $G = 800$ kg/(m^2·s)，倾斜下降光管壁温随焓值的变化。从图中可以看出，与亚临界压力区壁温分布不同，倾斜下降管从上母线到下母线均发生了两次壁温飞升。发生上述现象，一方面是因为随着压力逐渐接近临界值，汽水两相的密度差迅速减小，导致浮力作用迅速减弱，减小了上下母线区域换热条件的差异；另一方面，压力的提高，不仅使得汽泡更容易产生，而且削弱了液膜的稳定性，减弱了液膜厚度不均匀的影响，使下母线区域的液膜更容易被汽芯撕碎。

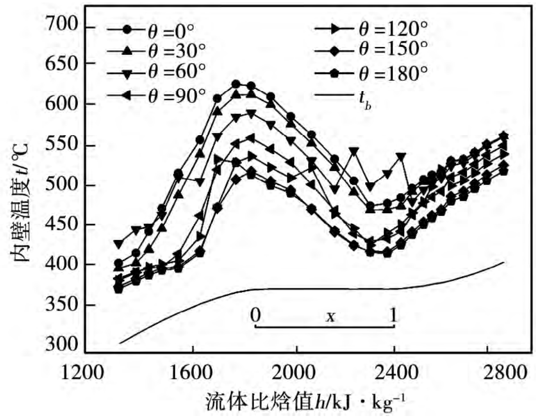

图 6　近临界压力区倾斜下降管周向内壁温随焓值变化

Fig. 6 Changes of the inner wall temperature of the oblique downcomer nearing the critical pressure zone along the circumferential direction with the enthalpy

如图 7 可知压力 $p = 20.5$ MPa，质量流速 $G =$ 800 kg/(m^2·s) 时，热负荷对上下母线处的壁温随焓值变化的影响。从图中可以看出，当热负荷从 250 kW/m^2 增加到 418 kW/m^2，上下母线处的壁温、壁温峰值以及温差都增大，但与亚临界压力区相比，上下母线处的临界干度的差值很小。当 $q = 250$ kW/m^2 时，$q/G = 0.312\ 5$，略小于图 4 中的相应值，但在图 4 中下母线处并未在低干度时出现壁温飞升。由此可见，在近临界压力区，虽然倾斜下降管内传热的周向不均匀性仍然存在，但浮力作用有所减弱，使上下母线处的壁温曲线具有相似性。

2.3　超临界压力区传热特性

图 8 示出了压力 $p = 22.5$ MPa，热负荷 $q = 418$ kW/m^2，质量流速 $G = 1\ 000$ kg/(m^2·s)，倾斜下降光管内壁温度随焓值的变化规律。从图中可以看出，在低焓值区和拟临界焓值区，上母线处的壁温明显高于其他母线处；当工质焓值在 1 800 ~ 2 500 kJ/kg 之间时，各条母线处的壁温曲线变化十分平坦，表明在该工况下，超临界水物性的急剧变化使拟临界焓值区的传热过程发生了强化。另外，在高焓值区，上母线处的壁温有所降低，使其与其它母线处的

温差减小，发生上述现象，主要是由于在高焓值区流体密度变化非常小，近壁面流体和主流的密度差可以忽略，使浮力作用减小的缘故。

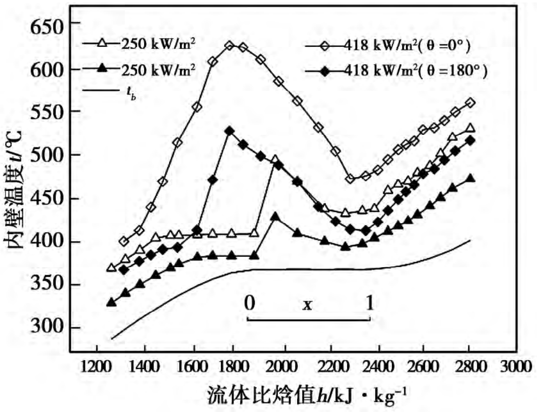

图 7 热负荷对内壁温度的影响

Fig. 7 Effect of the heat load on the inner wall temperature

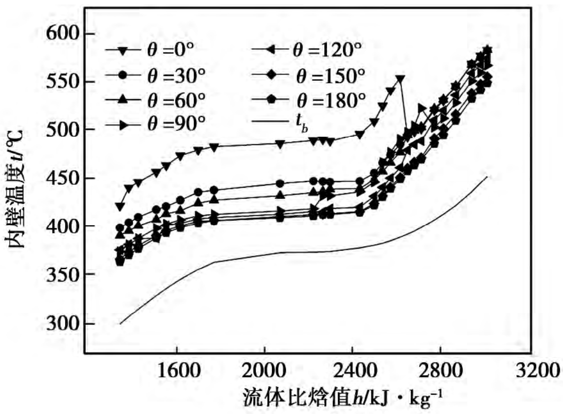

图 8 超临界区倾斜下降管周向内壁温随焓值变化

Fig. 8 Changes of the inner wall temperature of the oblique downcomer in the supercritical pressure zone along the circumferential direction with the enthalpy

图 9 示出了压力 $p=22.5$ MPa，质量流速 $G=1\ 000$ kg/(m^2·s) 时，热负荷对上下母线处的内壁温度随焓值变化的影响。如图所示，热负荷增大，上下母线处的壁温及温差迅速增加，这表明，在超临界压力区，增大热负荷具有与亚临界压力区相同的作用。

Pioro 指出，超临界压力下，工质在拟临界焓值区究竟发生传热恶化还是传热强化要根据试验工况条件而定[6]。Ackerman 也认为，当工质的拟临界温度在工质自身温度和管壁温度之间时，传热过程的发展是不可预测的[7]。在本次试验中，各个工况在拟临界焓值区均只观察到了不同程度的传热强化，当压力越靠近临界点，超临界水物性的剧烈变化引起的强化传热作用越显著。

从图 10 可以看出，在拟临界焓值区，22.5 MPa 工况的热负荷较高，但其下母线处的壁温非常接近 24 MPa 工况的下母线处的壁温，上母线处的壁温则明显低于后者；而在拟临界区以外的焓值区，高热负荷工况 22.5 MPa，160 kJ/kg 下的壁温高。这说明在拟临界焓值区，通过工质物性变化表现可看出压力的影响超过了热负荷，并且改变了壁温曲线的变化规律；而在拟临界区以外的焓值区中，热负荷是传热过程的主导因素。因此，对于倾斜下降管上母线来说，在拟临界焓值区，即使热负荷较低，但当压力较高时，也有可能出现壁温偏高的情况；若要在拟临界焓值区观察到传热恶化现象，则需要较大的热负荷值，并且压力越接近临界点压力，该临界热负荷值越大。

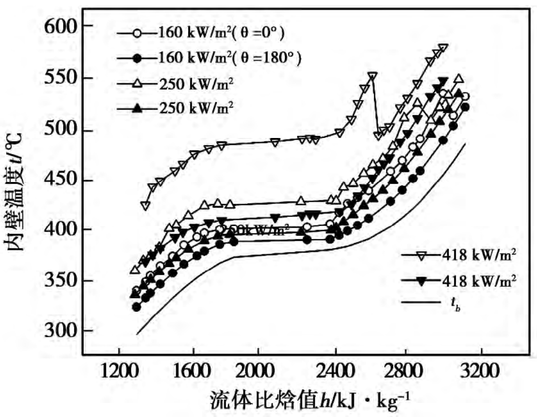

图 9 热负荷对内壁温度的影响

Fig. 9 Effect of the heat load on the inner wall temperature

2.4 试验关联式

2.4.1 亚临界和近邻界压力区

通过对亚临界和近邻界压力区试验数据拟合，得到上述两个压力区的临界干度关联式分别为：

$$x_{cr} = 1.5348 \cdot q^{-0.255} \cdot G^{0.1294} \cdot e^{0.1342(P/P_{cr})} \quad (1)$$

$$x_{cr} = 147.426 \cdot q^{-0.486} \cdot G^{0.614} \cdot e^{-6.83(P/P_{cr})} \quad (2)$$

式(1)的相对平均误差为 10.9%。适用范围：压力 $P=11.5\sim18$ MPa；质量流速 $G=450\sim900$ kg/(m^2·s)；外壁热负荷 $q=50\sim418$ kW/m^2；式(2)的平均相对误差为 11.26%，适用范围：压力 $P=20.5\sim21$ MPa，质量流速 $G=800\sim1\ 000$ kg/(m^2·s)；外壁热负荷 $q=167\sim418$ kW/m^2。

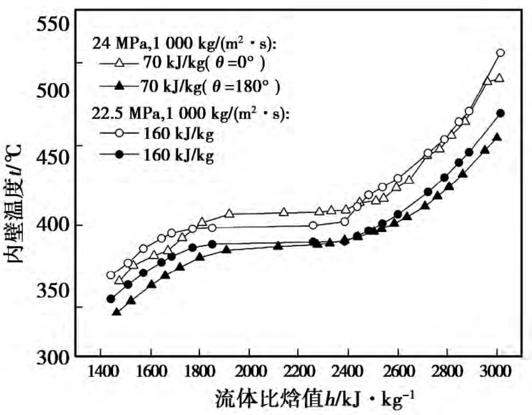

图 10　超临界压力区压力对上下母线壁温随热负荷变化的影响

Fig. 10 Effect of the pressure in the supercritical pressure zone on changes of the wall temperature on the top and bottom surface with the heat load

2.4.2　超临界压力区

根据已有研究成果，对超临界压力下得到的传热实验数据进行拟合，得到超临界压力区倾斜下降光管内壁面与工质之间的换热系数试验关联式如式(3)和式(4)所示:

上母线处的传热关联式为:

$$Nu_b = 0.003\,259\,Re_b^{0.824}\,Pr_b^{0.242}\left(\frac{\rho_w}{\rho_b}\right)^{0.156}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.341} \tag{3}$$

下母线处的传热关联式为:

$$Nu_b = 0.076\,23\,Re_b^{0.6256}\,Pr_b^{0.596}\left(\frac{\rho_w}{\rho_b}\right)^{0.634}\left(\frac{\lambda_w}{\lambda_b}\right)^{0.260} \tag{4}$$

式(3)、式(4)的均方根误差分别为 16.58% 和 18.43%，适用范围: 压力 $p = 22.5 \sim 28$ MPa，质量流速 $G = 1\,000 \sim 1\,550$ kg/($m^2 \cdot s$)；热负荷 $q = 160 \sim 585$ kW/m^2。

3　结　论

(1) 亚临界压力区内倾斜下降管上母线区域发生两次壁温飞升，下母线区域仅在高干度时发生一次壁温飞升，这两个区域的壁温分布明显不同，临界干度的差值也较大;

(2) 近临界压力区内壁温分布仍存在周向不均匀性，但上下母线区域的差别减小，临界干度的差值降低;

(3) 超临界压力下，管内传热过程在拟临界焓值区发生强化。对倾斜管上母线而言，在拟临界焓值区内，有可能出现高压低热负荷工况的管壁温度高于低压高热负荷工况的情况;

(4) 压力变化通过工质物性改变影响传热过程，进而影响内壁温度曲线的分布。在压力临界点或拟临界压力区域，倾斜管壁温特性由热负荷或质量流速与压力影响的相对大小共同决定;

(5) 通过对试验数据的处理，在亚临界和近邻界压力区，得到了倾斜下降管临界干度试验关联式; 在超临界压力区，得到了倾斜下降管上下母线处的传热系数试验关联式。

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(刘　瑶　编辑)

and particle diameter correlation formula. It has been found that the atomization flow rate, atomization angle and pressure are in a direct proportion and the atomization particle diameter and the atomization pressure are in a negative proportion. The flow characteristics and the atomization particle diameter exercise a big influence on the diameter of the aperture of the nozzle, the bigger the diameter of the aperture, the smaller the atomization angle influenced by the pressure. The test results can offer guidance for applications of water mist in controlling the dust. **Key words:** wet type dust removal system, low pressure dust removal nozzle, atomization characteristics, curve fitting

离心泵转速剧烈波动时的瞬时响应特性研究 = Study of the Transient Response Characteristics of a Centrifugal Pump Undergoing a Drastic Fluctuation in the Rotating Speed [刊, 汉] ZHAO Yan-juan (School of Information Engineering, Quzhou College of Vocational Technology, Quzhou, China, Post Code: 324000), ZHANG Yu-liang (School of Mechanical Engineering, Quzhou College, Quzhou, China, Post Code: 324000) //Journal of Engineering for Thermal Energy & Power. -2016, 31(5). -106~112

To reveal in-depth the transient response characteristics of a centrifugal pump when it has a drastic fluctuation of the rotating speed, set up was a circulating pipeline system, including a set of low specific speed centrifugal pump. According to the function defined by users themselves, sliding mesh method and RNG $k-\varepsilon$ turbulent flow model, an unsteady flow self-coupling numerical calculation was performed of the whole system. It has been found that the flow rate response lags behind the rotating speed variation course while the head response features a relatively good nature to follow up the rotating speed variation. The interference between the rotor and stator inside the turbomachinery exercises a most notable influence on the pressure at the outlet of the pump in the stage of the rotating speed acceleration and the pressure at the inlet of the pump in the stage of the rotating speed deceleration, however, exerts a relatively small influence on the flow rate and the power needed by the impeller. The evolution of the transient flow field in the process of the fluctuation in the rotating speed totally lags behind the quasi-steady state calculation results. The forgoing can offer important reference for revealing the transient response characteristics of a centrifugal pump. **Key words:** centrifugal pump, rotating speed drastic fluctuation, self-coupling calculation, transient response, quasi-steady state assumption

跨临界压力下倾斜下降管内水的传热特性试验研究 = Experimental Study of the Heat Transfer Characteristics of Water in an Oblique Downcomer at a Trans-critical Pressure [刊, 汉] WANG Si-yang, XIE Bei-bei, WANG Long, YANG Dong (National Key Laboratory on Multi-phase Flow in Power Engineering, Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) //Journal of Engineering for Thermal Energy & Power. -2016, 31(5).

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Experimentally studied were the heat transfer characteristics of water in an oblique bare downcomer with an inclination angle of 45 degrees at a pressure, a mass flow speed and an external wall heat load ranging from 11.5 ~ 28 MPa, 450 - 1 550 kg/(m^2·s) and 50 - 585 kW/m^2 respectively. The test results show that the wall temperature of the oblique downcomer features a non-uniform distribution along the circumferential direction of the tube. In the subcritical pressure zone, the wall temperature on the top and bottom surface of the oblique downcomer is obviously different and the dryness difference between the top and bottom surface of the oblique downcomer is comparatively big when the wall temperature soars. In the nearing critical pressure zone, the wall temperature distribution at various top and bottom surfaces of the oblique downcomer is similar and the dryness difference between the top and bottom surface of the oblique downcomer is very small when the wall temperature skyrockets. In the supercritical pressure zone, the heat transfer is intensified in the quasi-critical pressure zone and under some operating conditions, the influence of the pressure may change the action of the heat load. In the high enthalpy value zone, the wall temperature on the top surface of the oblique downcomer may somewhat decrease. On the basis of the test results, a critical dryness correlation formula in the subcritical and nearing critical pressure zone and an intensified convection heat transfer correlation formula at a supercritical pressure were obtained. **Key words:** oblique downcomer, wall temperature, pressure, heat load

350 MW **超临界** W **火焰炉拱部/墙部风配比研究** = **Study of the Proportion of the Air Distribution Between the Arch and Wall Portion in a** 350 **MW Supercritical Multi-ejection Staged Combustion W-shaped Flame Boiler** **[刊,汉]** ZHU Qun-yi, ZENG Ling-yan, CHEN Zhi-chao (College of Energy Science and Engineering, Harbin Institute of Technology, Harbin, China, Post Code: 150001), ZONG Qiu-dong (Shandong Electric Power Engineering Consultancy Institute Co. Ltd., Jinan, China, Post Code: 250013), KUANG Min (College of Sea Transportation, Ningbo University, Ningbo, China, Post Code: 315211) //Journal of Engineering for Thermal Energy & Power. -2016, 31(5). -118 ~ 123

For a 350 MW newly built supercritical W-shaped flame boiler adopting the multi-ejection staged combustion technology, the influence of the ratio between the secondary air flow rate passing through the arch portion and the tertiary air flow rate passing through the wall portion (R2/R3) on the in-furnace flow, combustion and NOx formation was investigated when the ratio above mentioned was 15%/43.89%, 25%/33.89%, 28.35%/30.54% and 35%/23.89% respectively. It has been found that when R2/R3 is 15%/43.89%, the flow field inside the furnace is mis-