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平行流蒸发器内气液两相流分配均匀性实验研究

李夔宁, 吴小波, 尹亚领
(重庆大学 动力工程学院, 重庆 400030)

摘　要: 平行流蒸发器内气液两相(特别是液相)在各扁管间的分配对其传热性能影响较大, 如果各扁管间的气液分配不均匀其传热性能将显著地下降。在不同气－液流量下实验研究了 6 种不同形式的平行流蒸发器的分支管液体流量分配情况, 实验中观察到流型以环状流为主。研究发现, 对于竖直向下流动和竖直向上流动, 用通过增加管径的方法不能改善液体流量在各分支管的分配, 而主管中气液入口的位置对于流量分配均匀性影响较大。

关　键　词: 平行流蒸发器; 气－液两相流量; 流型; 均匀性; 环状流

中图分类号: TK124; O359.1　　　文献标识码: A

引　言

多孔扁管换热器空气侧采用换热性能较高的百叶窗翅片, 制冷剂侧采用小水力直径的多通道扁管, 使空气侧和制冷剂侧的换热都被强化, 被认为是一种高效、紧凑的换热器。平行流换热器已广泛应用于汽车空调系统中的冷凝器, 近年来又被推广应用到家用空调、冰箱的蒸发器, 以取代传统的翅片圆管换热器[1~2]。平行流蒸发器内气液两相(特别是液相)在各扁管间的分配对其传热性能影响较大, 如果各扁管间的气液分配不均其传热性能将显著的下降[3]。Tushar Kulkarni 人等的研究发现[4], 下降可高达20%。在平行流冷凝器中传热恶化现象没有蒸发器严重, 因为进入冷凝器的是单相气态工质相比进入蒸发器的气液两相工质, 流动均匀分配较容易达到。另一方面由于平行流蒸发器为了方便冷凝水的导出, 采用了水平集管的设计(冷凝器是垂直集管, 下面讨论的竖直向下流动和向上流动指的是流体在分支管的流向, 集管仍是水平的, 并不矛盾), 水平集管内两相流体容易受重力的影响形成分层流动。

Nae-Hyun Kim、Jun Kyoung Lee、A. Marchitto 和 Hai-tao Hu 等人实验研究了影响平行流蒸发器内气液两相流动分配的各种因素[5~8]。由于平行流换热器各分支管内液体流量分配是影响换热的主要因素, 所以本实验通过改变平行流蒸发器布置形式、进出口管径等, 得到不同气液流量下每根分支管的液体流量占总液体流量的比例, 观察相应的流型, 并且比较布置形式、进出口管径等在不同气液流量下对平行流蒸发器内液体流量分配的影响。

1　实验装置

实验装置示意图如图 1 所示, 实验由气路、水路、气－水混合后的主管路以及称重测量系统组成。水路由水箱、液泵、液体流量计和流量调节阀组成, 其中液体流量计为液体涡轮流量计, 精度等级: ±1%。气路由压力调节阀和气体流量计组成, 其中气体流量计为气体涡轮流量计, 精度等级: ±1%。气－水混合后的主管路由混合段、压力表、集管和分支管组成, 其中为保证进入集管的两相流体充展, 从混合段到集管进口的管路长 1.2 m。称重系统由气液分离器和电子秤组成, 其中电子秤的精度: ±0.02%。实验用室温的空气－水作为气－液工质。

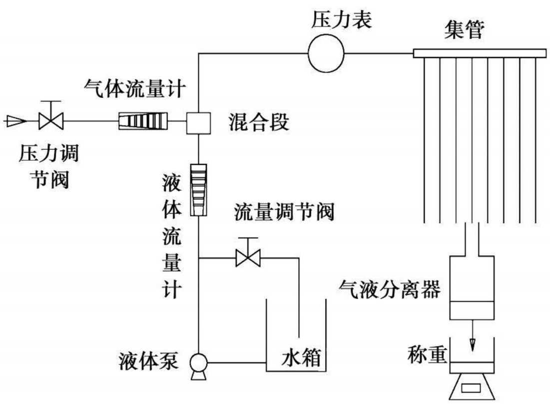

图 1　实验装置示意图

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作者简介: 李夔宁(1970－), 男, 重庆人, 重庆大学副教授.

图 2 为 6 种不同的进出口通道布置形式，均用透明的 PVC 制作，可以可视化观察主管内的两相流动状态。主管均为长 135 mm，内径 20 mm 的圆管。8 根分支管均用圆管代替实际的扁平管，间距 16 mm，长 700 mm。图 2(a)～(c)所示两相流体从右段进入，图 2(d)～(e)所示两相流体从与分支管所对的主管直管段中间内径 10 mm 的管进入，图 2(f)所示两相流体从与分支管夹角 135°的内径 10 mm 的管进入。图 2(a)、(d)、(f)所示分支管内径均为 3 mm，图(b)所示左边 4 根管内径为 3.5 mm，其余为 3 mm，图(c)所示左边 4 根管内径为 3 mm，其余为 3.5 mm，图(e)所示中间 4 根管内径为 3 mm，其余为 3.5 mm。

本实验气水混合物进口质量流量和干度范围分别是：80.5～120.5 kg/(m^2·s)，0.05～0.15。

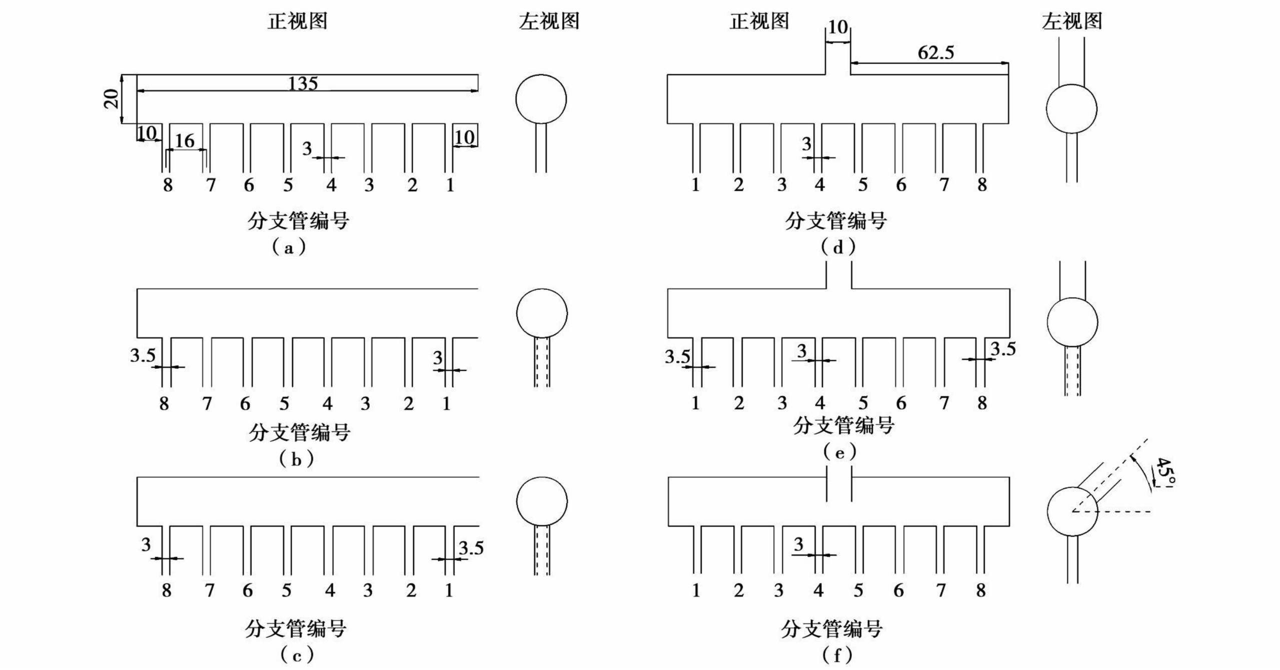


图 2　进出口通道布置形式(mm)

2　实验结果及讨论

2.1　竖直向下流动

2.1.1　液体质量流量和干度对图 2(a)所示布局的分支管液体流量分配的影响

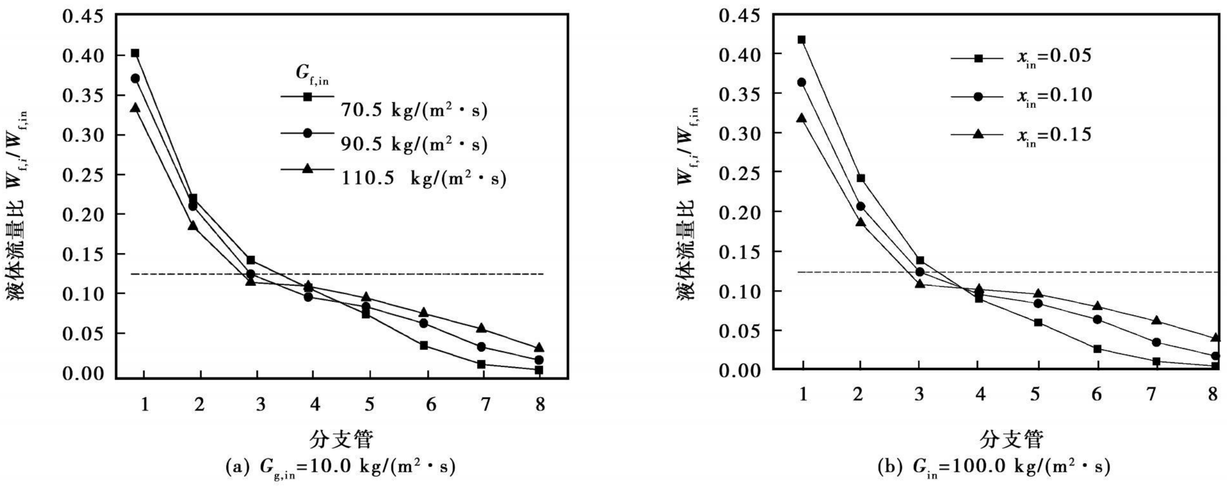


图 3　液体质量流量($G_{f,in}$)和干度(x_{in})对图 2(a)所示布局液体流量分配的影响

图 3 中横坐标表示分支管号(图 4～图 12 图示坐标意义和此相同)，与图 2(a)的所标示分支管号相对应；纵坐标表示液体流量比(图 4～图 12 图示坐标意义相同)，即第 i 根管的液体质量 $W_{f,i}$ 与总液

体质量 $W_{f,in}$的比值; 图中虚线表示液体流量在每根分支管中均匀分配时, 达到的流量比; 图 3 中气体流量固定为 $G_{g,in}=10.0\ kg/(m^2s)$, 进口总质量流量固定为 $G_{in}=100.0\ kg/(m^2s)$。图 3(a)为液体质量流量的变化对图 2(a)所示布局的分支管液体流量分配的影响, 当液体流量增加时, 前 4 根管的流量比减小, 后 4 根增加。图 3(b)为干度变化对图 2(a)所示布局的分支管液体流量分配的影响, 当干度增加时出现了与液体流量增加时相类似的结果。通过可视化观察发现, 此时管内流动属环状流动。当液体或气体流量增加时, 主管上部液膜变厚、气－液动量增加, 此时将有更多的液体被带往与进口相对的后方, 从后 4 根管流出。

2.1.2　液体质量流量和干度对图 2(b)所示布局的分支管液体流量分配的影响

图 2(b)所示布局与图 2(a)的区别为与进口相对的后 4 根管内径为 3.5 mm, 液体质量流量和干度对图 2(b)所示布局液体流量分配的影响如图 4 所示。由于后 4 根管管径变大, 阻力变小, 所以在相同情况下, 图 2(b)所示布局前几根管流量减少, 后几根增加。对比图 3 和图 4 发现当液体流量或干度较小时, 图 2(b)所示布局与图 2(a)所示布局差别较小; 当液体流量或干度较大时, 差别较大。从图 4(b)可以看出: 当干度 $x=0.15$ 时, 第 2～第 6 根分支管彼此相差不大。但是从总体看这种改变后 4 根管径的做法, 效果不明显, 从图 4 看出各分支管液体流量差别仍然很大。

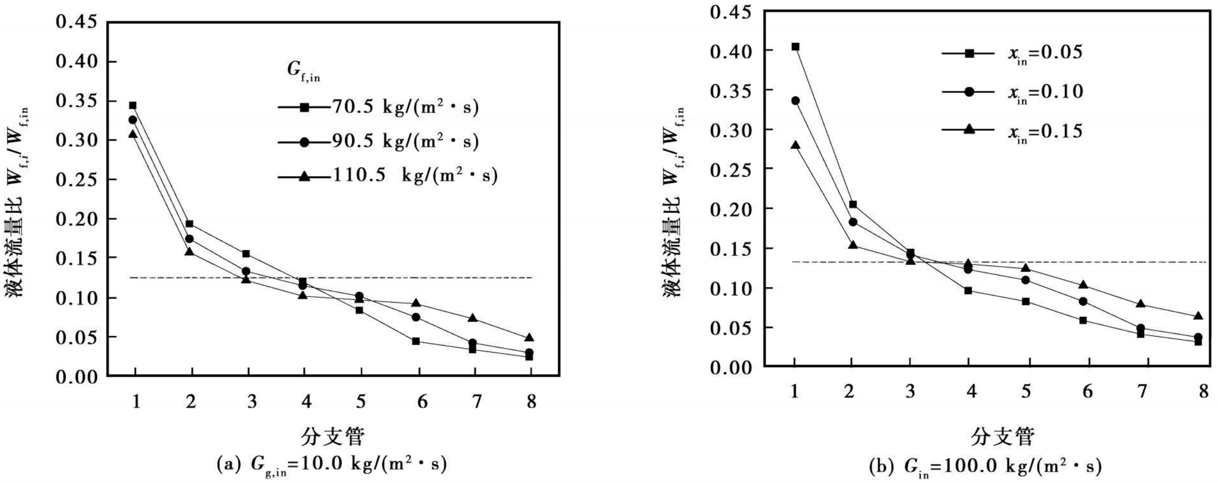


图 4　液体质量流量和干度对图 2(b)所示布局液体流量分配的影响

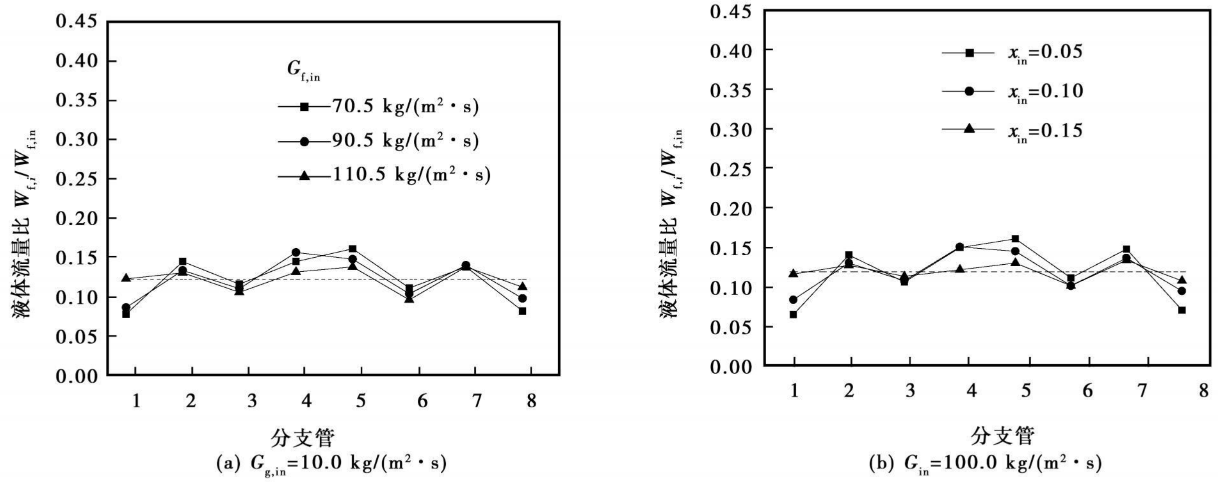


图 5　液体质量流量和干度对图 2(d)所示布局液体流量分配的影响

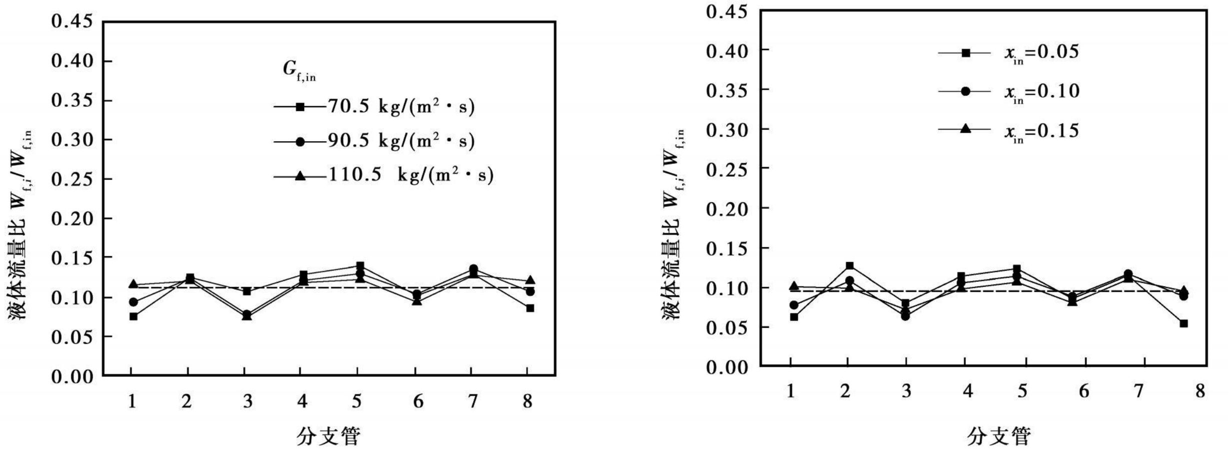
2.1.3　液体质量流量和干度对图 2(d)所示布局的

分支管液体流量分配的影响

图2(d)所示布局向下流动时液体流量比变化从图5中可以看出:气-液流量增加,位于中间管子的液体流量比减小,位于两边管子的液体流量比增加。如图5(a)中流体流量为110.5 kg/(m^{2}s)和图5(b)干度为0.15时,各分支管的液体流量分配差别很小。通过可视化观察发现,此时主管内从中间向两旁形成波状、起伏流动、上部液膜较薄,大概在第2、5、7管位置形成波峰,这就造成了如图5所示液体流量比成波状变化,第2、5、7管的液体流量比较大。且当气-液流量增加时波状流动向两旁以更快的速度传递,所以位于中间管子的液体流量比减小,位于两边管子的液体流量比增加。

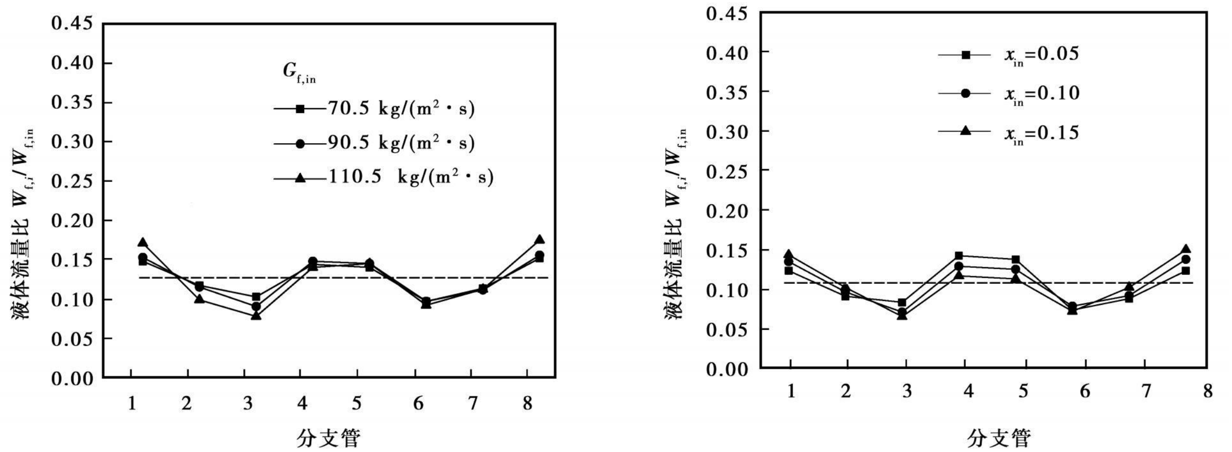
2.1.4 液体质量流量和干度对图2(e)所示布局的分支管液体流量分配的影响

图2(e)所示布局与图2(d)的区别为距离进口管两旁最远的4根管内径为3.5 mm。由于距离进口管两旁最远的4根管内径变大,阻力变小,所以在相同情况下,图2(e)所示布局中间几根管流量减少,其它几根增加。对比图5和图6发现在相同的气液流量下图2(e)所示布局的两旁分支管流体流量比小幅度增加,中间减少。图2(e)所示布局,由于主管内从中间向两旁形成波状、起伏流动,大概在第2和第7管位置形成波峰,第3和第6管位置形成波谷,而第2和第7管内径3.5 mm,而第3和第6管内径3 mm。这就造成了如图6所示第2和第3、第6和第7根管的液体流量比相差较大。



(a) $G_{g,in}$=10.0 kg/(m^2·s)　　(b) G_{in}=100.0 kg/(m^2·s)

图6　液体质量流量和干度对图2(e)所示布局液体流量分配的影响



(a) $G_{g,in}$=10.0 kg/(m^2·s)　　(b) G_{in}=100.0 kg/(m^2·s)

图7　液体质量流量和干度对图2(f)所示布局液体流量分配的影响

2.1.5 液体质量流量和干度对图2(f)所示布局的分支管液体流量分配的影响

图 2(f)所示布局竖直向下流动时液体质量流量对液体流量比的影响从图 7(a)中可以看出：当液体质量流量增加时，两端管子的液体流量比增加，中间两根管虽然流量有所增加，但是液体流量比几乎没变化。由图 7(b)所示，当干度增加时中间两根管子的液体流量比减少，靠近端面的管子液体流量比增加。原因为：图 2(f)所示进口管与分支管夹角 135°，有一部分两相流体直接落到管底，剩余的撞击在管壁上，沿着管壁下落。当气体或液体流量增加时，撞击管壁后的气或液体轴向动量增加，靠近端面管的流量就增加。

2.2　竖直向上流动

2.2.1　液体质量流量和干度对图 2(a)所示布局的分支管液体流量分配的影响

对于图 2(a)所示的布置形式向上流动时液体质量流量和干度对液体流量分配的影响如图 8 所示。由于形成环状流动，且受重力的影响，主管上部的液膜厚度随着流体运动的方向减小，下部液膜厚度随着流体运动的方向增加。所以流量分配趋势是前几根管减小，后几根渐大。当气或液的流量增加时，主管上部液膜增厚，所以前几根管液体流量比增加，后几根减少。

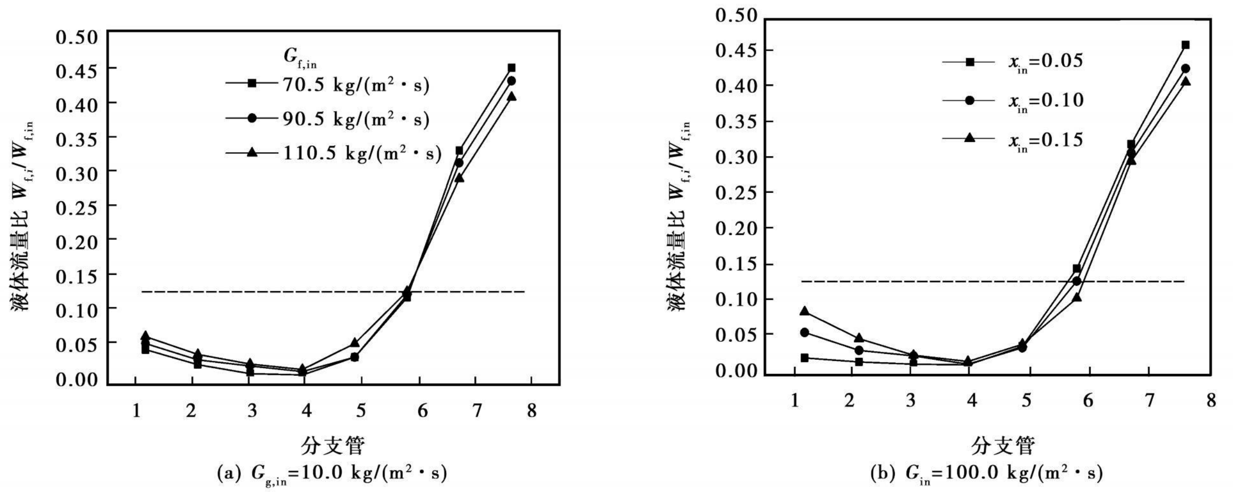


图 8　液体质量流量和干度对图 2(a)所示布局液体流量分配的影响

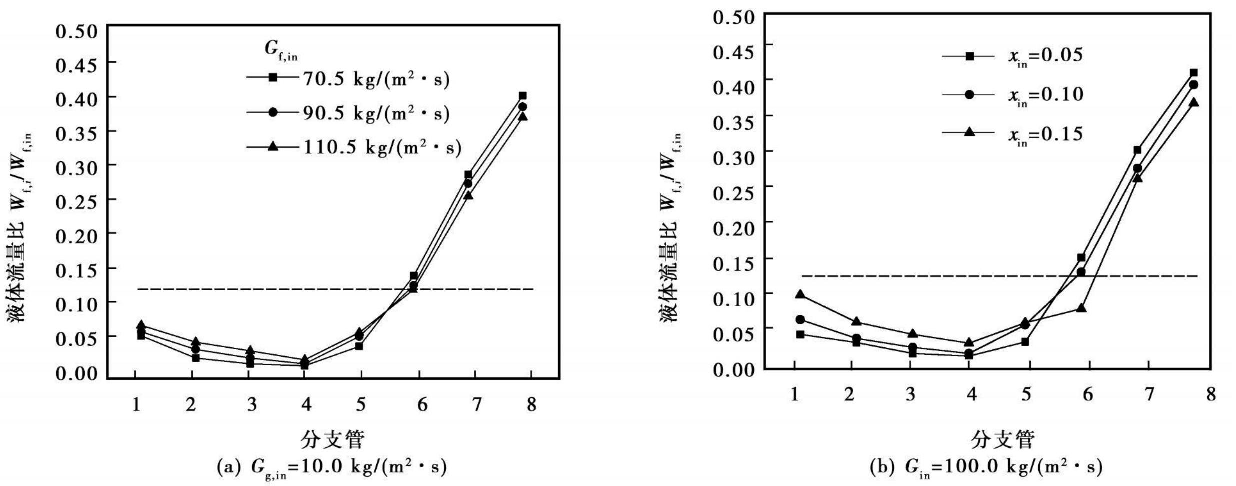


图 9　液体质量流量和干度对图 2(c)所示布局液体流量分配的影响

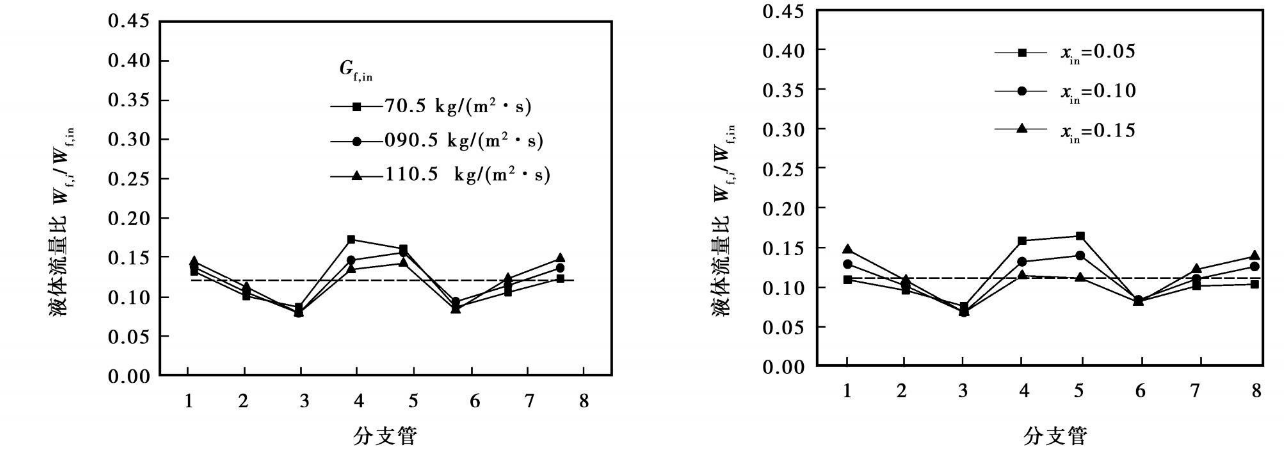
2.2.2　液体质量流量和干度对图 2(c)所示布局的分支管液体流量分配影响

图 2(c)所示布局与图 2(a)的区别为靠近进口管的 4 根管内径为 3.5 mm。由于靠近进口根的 4 根管内径变大，阻力变小，所以在相同情况下，图 2(c)所示布局前几根管流量增加，后几根减少。对比图 8 和图 9 发现当液体流量或干度较小时，图 2(c)所示布局与图 2(a)所示布局差别较小；当液体流量

或干度较大时，差别较大。从图 9(b)可以看出：当干度 $x=0.15$ 时，第 2～第 5 根分支管彼此相差不大。但是从总体看这种改变靠近进口的 4 根管管径的做法，效果不明显，从图 9 看出各分支管液体流量差别仍然很大。

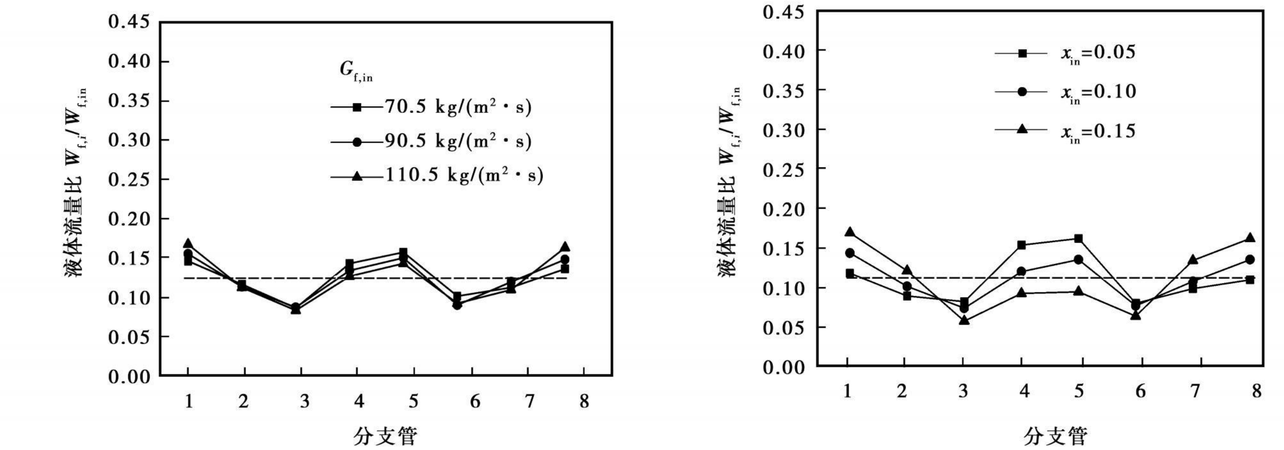
2.2.3　液体质量流量和干度对图 2(d)所示布局的分支管液体流量分配的影响

图 2(d)所示布局向上流动液体流量比变化从图 10 中可以看出：气－液流量增加，位于中间管子的液体流量比减小，位于两边管子的液体流量比增加。如图 10(a)中流体流量为 110.5 kg/(m^{2}s)和如图 10(b)干度为 0.15 时，各分支管的液体流量分配差别较小。通过可视化观察发现，此时主管内形成环状流动，管上部液膜厚度从中间向两旁减小，由于重力的影响其减少速度较快；管下部液膜厚度较厚且从中间向两旁增加。这就形成了如图 10 所示的流量比总体变化趋势，由于上部液膜是由气－液撞击上管壁形成，当气或液流量增加时，致使上部液膜厚度变薄，所以位于中间管子的液体流量比减小，位于两边管子的液体流量比增加。



(a) $G_{g,in}$=10.0 kg/(m^2·s)　(b) G_{in}=100.0 kg/(m^2·s)

图 10　液体质量流量和干度对图 2(d)所示布局液体流量分配的影响



(a) $G_{g,in}$=10.0 kg/(m^2·s)　(b) G_{in}=100.0 kg/(m^2·s)

图 11　液体质量流量和干度对图 2(e)所示布局液体流量分配的影响

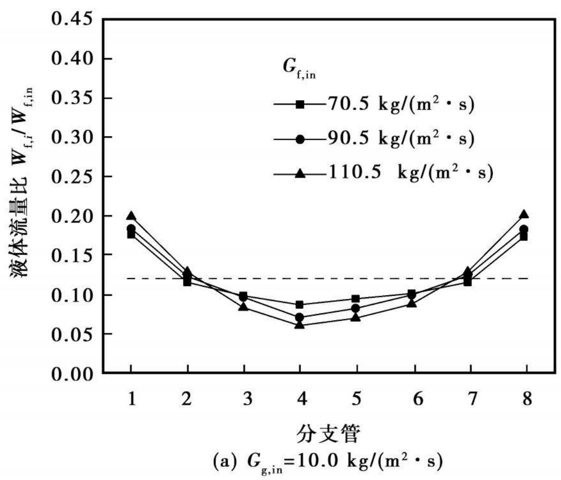
2.2.4　液体质量流量和干度对图 2(e)所示布局的分支管液体流量分配的影响

对比图 10 和图 11 发现，在相同的气液流量下图 2(e)所示布局的两旁分支管流体流量比小幅度增加，中间减少。可以从图 11(a)看出，当液体流量增加时中间两根管的液体流量比下降速率较小；从图 11(b)看出，当干度增加时中间两根管的液体流量比下降速率较大，当干度为 0.15 时中间两根管的液体流量比已经低于均匀分配水平，两旁分支管的气液流量比较大，所以从均匀分配的目的来说这种

布置形式不如图 2(d)。

2.2.5　液体质量流量和干度对图 2(f)所示布局的分支管液体流量分配的影响

图 2(f)所示布局竖直向下流动时液体质量流量和干度对液体流量比的影响从图 12 中可以看出: 当气或液质量流量增加时, 两端管子的液体流量比增加, 中间两根管液体减少, 但是减少的幅度不大。原因为: 图 2(f)所示进口管与分支管夹角 135°, 竖直上升时两相流体直接撞击在管壁上, 由于重力的影响, 只有一小部分流体沿着管壁向上, 形成卷吸; 大部分流体沿着管壁下落与底部液膜一起向管两旁流动。所以形成图 12 的总体变化趋势。当气体或液体流量增加时, 撞击管壁后的气或液体轴向动量增加, 向上流动的液体没有向下流动的液体增加的多, 所以靠近端面管的流量就增加。



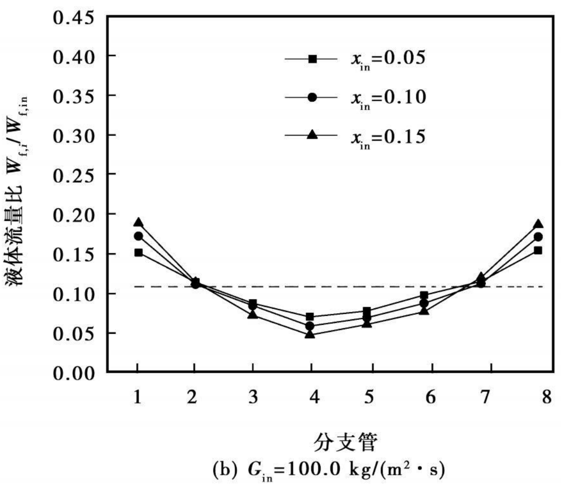


图 12　液体质量流量和干度对图 2(f)所示布局液体流量分配的影响

3　结　论

实验通过测量 6 种不同结构形式的平行流蒸发器, 在不同气—液流量和干度下的各分支管的液体流量比, 以及观察相应的流型, 得到的主要结论为:

(1) 不论是在竖直向下流动时还是在竖直向上流动时, 通过增加分支管的内径来调节液体流量在各分支管的分配, 其均匀性改善不大, 有时反而恶化;

(2) 不论是在竖直向下流动时还是在竖直向上流动时, 两相流体入口应尽可能布置在集管的中间而不是侧端, 这样更有利于液体流量在各分支管内的均匀分配;

(3) 在向下流动时, 图 2(f)的布置形式效果虽然没有图 2(d)好, 但在实际应用中可以作为一种替代, 但是在向上流动时效果比图 2(d)差得多;

(4) 实验发现集管中的流型以环状流型为主, 在集管底部夹杂有波状流。

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transversely sweeping across a circular cylinder and a square one, the authors have identified the vortex street shedding frequency and the variation of Strouhal number. During the test, the Reynolds number ranges from 0.9×10^4 to 2.3×10^4 and the sectional gas content has a variation range of 0 to 0.2. The test results indicate that in a certain range of gas content, the vortex-street shedding frequency and Strouhal numbers of the two types of cylinders will increase with an increase of the sectional gas content. The increment gradient of the square cylinder Strouhal number is independent of the Reynolds number while that of the circular one is susceptible to the influence of the Reynolds number. **Key words**: gas-liquid two-phase flow, tube-wall pressure-difference method, square cylinder, circular cylinder, vortex street

气固两相 Y 型分支管网流量分配特性的试验研究与数值模拟＝**Experimental Study and Numerical Simulation of the Flow Distribution Characteristics of a Gas-solid Two-phase Y-shaped Branch Pipe Network**[刊, 汉] /DUAN Guang-bin, HU Shou-gen, ZHAO Jun, et al (College of Energy Source and Power Engineering, Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093)//Journal of Engineering for Thermal Energy & Power. —2009, 24(6). —750～755

By using compressed air as conveyance power and millet as a transport medium in horizontal Y-shaped branch pipes, the solid flow distribution characteristics of the above pipes were studied. The test results show that the change of the included angle between the central axial lines of the branch and main pipes as well as the superficial gas velocity have a relatively big influence on the solid-phase flow distribution characteristics. In the meantime, by adopting Euler-Lagrange two-phase flow research method and a discrete phase model (DPM) for the solid phase, the authors have employed Fluent software to numerically simulate the gas-solid two-phase flow in the Y-shaped branch pipes having three different included angles. The simulation results have predicted relatively well the flow pattern of particles at the branch points, the movement trajectory of the particles inside the branch pipes and the distance required for resuming a uniform distribution of the particle phase flow field. By comparing the numerical simulation results with the test ones of the solid particle mass distribution in the branch pipes, the authors have found that there exists a relatively small error between the two results. **Key words**: gas-solid two-phase flow, Y-shaped branch pipe, flow distribution characteristics, numerical simulation, included angle

热电联供系统中烟气冷凝传热性能试验研究＝**Experimental Study of the Condensation Heat Transfer Performance of Flue Gases in a Heating-and-power Cogeneration System**[刊, 汉] /ZHAO Xi-ling, FU Lin, ZHANG Shi-gang, et al (Building Technology and Science Department, Tsinghua University, Beijing, China, Post Code: 100084)//Journal of Engineering for Thermal Energy & Power. —2009, 24(6). —756～758

Concerning the problem of the inability to fully recover the waste heat in flue gases, experimentally studied was a flue gas condensation heat recovery device of an innovative heating-and-power cogeneration system that could fully recover the waste heat in flue gases. In this connection, the research emphasis was laid on the heat transfer performance of a smooth tube flue-gas condensing equipment item under the relevant operating condition. The research results indicate that under the test operating condition, the heat transfer coefficient of the dry type condensing section can be as high as 60 W/(m^2·K) with that of the condensing section being 90 to 100 W/(m^2·K). The heat transfer coefficient of the condensing section is about 1.5 to 1.7 times that of the dry type one. The authors have also worked out a heat transfer criterion-based relational expression under the operating condition, thus providing an underlying basis for popularizing the design and operation of the system in question. **Key words**: heating-and-power cogeneration, flue gas, condensation heat, latent heat, heat transfer performance

平行流蒸发器内气液两相流分配均匀性实验研究＝**Experimental Study of the Distribution Uniformity of the Gas-liquid Two-phase Flow in a Parallel Flow Evaporator**[刊, 汉] /LI Kui-ning, WU Xiao-bo, YIN Ya-ling (College of Power Engineering, Chongqing University, Chongqing, China, Post Code: 400030)//Journal of Engineering for Thermal Energy & Power. — 2009, 24(6). —759～765

The distribution of the gas-liquid two-phase flow (especially the liquid phase) in various flat tubes of a parallel flow evaporator exercises a relatively big influence on its heat transfer performance. If the gas and liquid distribution in various flat tubes is not uniform, the above-mentioned performance will deteriorate remarkably. At different gas and liquid flow rates, the authors have experimentally studied the liquid flow distribution in six forms of branch pipes of a parallel flow evaporator. During the test, it has been determined that the annular flow pattern predominates. It has been found that for a vertical descending and ascending flow, the method of increasing the tube diameter can not improve the liquid flow distribution in various branch pipes, but the location of the gas and liquid inlet in the main pipe has a relatively big influence on the uniformity of the flow distribution. **Key words**: parallel flow evaporator, gas-liquid two-phase flow rate, flow pattern, uniformity, annular flow

增压锅炉燃烧监测试验研究=**Experimental Study of the Combustion Monitoring of a Supercharged Boiler**[刊, 汉] /ZHOU Guo-yi (Marine and Power College, Naval Engineering University, Wuhan, China, Post Code: 430033), SUN Yi-peng, LOU Chun, et al (National Key Laboratory on Coal Combustion, Central China University of Science and Technology, Wuhan, China, Post Code: 430074)//Journal of Engineering for Thermal Energy &Power. — 2009, 24(6). —766 ~769

Supercharged boilers are key equipment items in a marine steam power plant and it is necessary to conduct a real-time monitoring of the in-furnace combustion to secure their good reliability and high cost-effectiveness. During the test, the authors have first employed an image acquisition system to capture the flame images at various loads of the boiler and then used image processing technology to obtain the radiation temperature of the flame and the radiant energy magnitudes characterizing the in-furnace combustion intensity. It has been found that during a normal operation, the boiler flame temperature is approximately 1700 K, while at a high load, the temperature is about 1900 K. The radiation temperature is in relatively good agreement with the numerical simulation results. In the meantime, it has been found by monitoring and analyzing the boiler flame radiant energy signals at six operating loads that the radiant energy signals assume a basically same variation tendency as the superheated steam and flue gas temperature, facilitating the introduction of the radiant energy into the control system as a feedback signal and thereby optimizing the boiler control. **Key words**: supercharged boiler, combustion monitoring, image processing, radiation temperature, radiant energy signal

“W”型火焰锅炉二次风改造对燃烧影响的试验研究=**Experimental Study of the Influence of the Secondary Air Modification of a “W” Type Flame Boiler on Combustion**[刊, 汉] / LEI Lin, DUAN Xue-nong (Experiment Research Institute, Hunan Provincial Electric Power Corporation, Changsha, China, Post Code: 410007), WANG Hua-jian (National Key Laboratory on Coal Combustion, Central China University of Science and Technology, Wuhan, China, Post Code: 430074), WANG Yi-gang (Datang Huayin Zhuzhou Thermal Power Generation Co. Ltd., Zhuzhou, China, Post Code: 412000)//Journal of Engineering for Thermal Energy &Power. — 2009, 24(6). —770 ~772

In the light of the problems and deficiencies of a “W” type flame boiler of FW (Foster Wheeler) technology at high loads, the authors have reconstructed a 1 025 t/h boiler of the same type in a power plant by decreasing the incidence angle of F-layer secondary air downward by 25 degrees. The problem and deficiencies include: a high combustible content of fly-ash at high operating loads, difficulty in combustion air replenishment and susceptibility to screen type superheater overheating, etc. Through a data simulation and a cold and hot state contrast test, it has been found that the advantages resulting from the reconstruction are evident at boiler high loads. At the rated load, primary air path is effectively lengthened and the above-mentioned problems, such as the air replenishment difficulty and overheating of the screen type superheater, have been solved or eliminated. The desuperheating water requirement is cut by 20.9% and the solid incomplete combustion loss decreases by over 1.5%. **Key words**: “W” type flame boiler, secondary air, combustion, reconstruction

基于数据融合的机组燃煤可磨性在线检测=**On-line Detection of Plant Fuel Coal Grindability Based on Data**