热力工程

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# $TiO_2$ 纳米颗粒对相变悬浮液流变和导热系数特性影响研究

靳 健[1], 刘沛清[1], 林贵平[1], 王龙[2]

(1. 北京航空航天大学 航空科学与工程学院, 北京 100191; 2. 利兹大学 颗粒科学与工程学院, 英国利兹 LS9 JT)

摘 要: 通过实验方法研究了掺入 $TiO_2$ 纳米颗粒的相变悬浮液粘性和导热系数。研究表明, 当纳米颗粒浓度不超过 5%时, 悬浮液仍可被视为牛顿流体, 悬浮液的粘性随纳米颗粒浓度增加以非线性方式增加; 当纳米质量颗粒浓度为 5%时, 相变悬浮液的粘性提高约 23%。纳米颗粒的加入能够显著提高相变悬浮液的导热系数, 当纳米颗粒质量浓度为 5%时, 相变悬浮液导热系数提高约 7%。当纳米颗粒浓度较低时, 纳米颗粒对相变悬浮液导热系数的提高幅度要高于对水的提高幅度。文中从不同方面分析了使用这种新型悬浮液作为传热工质的优势。

关 键 词: 相变微胶囊; 纳米颗粒; 纳米流体; 牛顿流体; 潜热

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## 引 言

微胶囊相变材料 (MPCM)是一种微米级颗粒 (粒径分布从几微米至数十微米)。颗粒内核是相变材料, 颗粒外壳通常用高分子聚合物, 将这种颗粒悬浮在液体介质中, 形成一种二元潜热型悬浮液。在相变材料发生相变时, 相变悬浮液具有较大热容, 且相变前后, 冷却液体积和流动结构不发生变化。因此, 这种冷却方式自从 20世纪 70年代末被提出后, 受到了人们的广泛关注[1－6]。

虽然相变悬浮液作为一种传热工质具有很多优点, 但是目前应用较多的相变材料是导热系数明显低于水的石蜡, 因此由石蜡颗粒和水制成的相变悬浮液有效导热系数低于水。如何提高相变悬浮液导热系数成为决定其大规模实际应用的关键问题。

纳米流体是通过在液体中加入纳米量级的金属或金属氧化物颗粒而制成的一种悬浮液。作为一种传热工质, 纳米流体具有导热系数高、性能稳定和系统压降增量小等优点。自从 1995年 Cho首次提出纳米流体的概念后[7], 纳米流体在强化传热领域的应用得到了越来越多研究人员的重视[8－11]。

鉴于相变悬浮液和纳米流体各自的传热特点, 如果将纳米颗粒加入到相变悬浮液中, 就可以得到一种包含两种颗粒的悬浮液, 该悬浮液将同时拥有较高的导热系数和较大的热容。以下简称这种新型悬浮液为 NMPCM悬浮液, 文中通过实验方法研究了 NMPCM悬浮液的粘性和导热系数, 并分析了加入纳米颗粒对提高相变悬浮液传热效果的作用。

## 1 实验方法

### 1.1 纳米流体的制备

图 1为两步法制备纳米流体的工艺流程图, $TiO_2$ 纳米颗粒和蒸馏水被用来制备纳米流体。

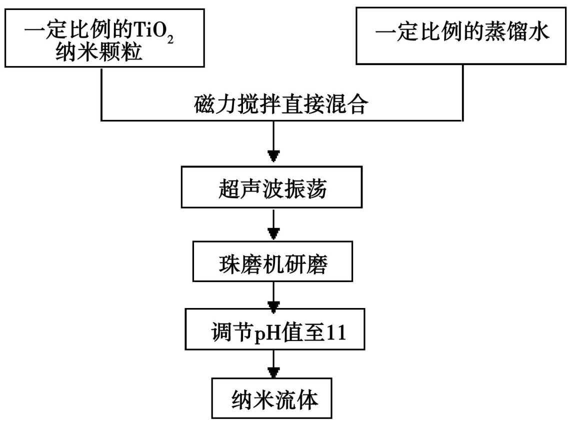


图 1 纳米流体的制备流程

由图 1可知, 首先将一定比例的 $TiO_2$ 纳米颗粒 (德国 Degussa公司生产 )和蒸馏水进行混合, 并

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作者简介: 靳 健 (1980－), 男, 河北霸州人, 北京航空航天大学博士研究生.

用磁力搅拌的方式使纳米颗粒在蒸馏水中分布均匀。由于此时纳米颗粒存在着明显的团聚,所以需要将这些团聚打散。首先利用超声波对悬浮液进行 1 h左右的振荡,对团聚进行初步的打散,然后利用珠磨机(Dyno Multi-Lab Mill, Willy A. Bachofen of Switzerland)对悬浮液进行进一步的研磨,如图 2所示。该珠磨机利用固定在壁面上的细小坚硬的圆柱对纳米颗粒进行研磨,在研磨过程中每隔 0.5 h对悬浮液进行采样测量粒径。进行约 4 h的研磨后,平均颗粒直径减至 100 μm左右时即满足要求。为了避免纳米颗粒重新团聚,将纳米流体的 pH值调至 11,这样在纳米颗粒间会存在较强的 Zeta电位,阻止颗粒重新团聚。图 3为 SEM显微镜下的纳米颗粒。

图 2　珠磨机外形

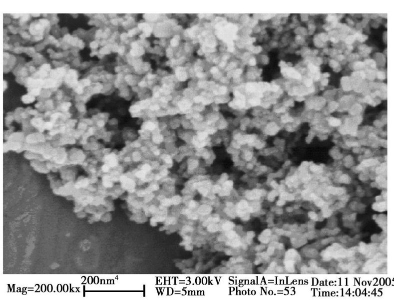


图 3　SEM显微镜下的纳米颗粒

### 1.2　NMPCM悬浮液的制备

为了保证悬浮液的稳定性,首先将相变悬浮液的 pH值调至 11,然后将相变悬浮液和纳米流体按一定的浓度比例混合,再利用磁力搅拌对悬浮液进行约 1 h的搅拌,得到分散均匀的 NMPCM悬浮液。通过观察可知,用上述方法制备出来的悬浮液可以稳定地存在 2周以上,图 4为 NMPCM悬浮液中的颗粒分布,其中较大的颗粒是微米量级的相变颗粒,而相变颗粒表面的白点是纳米颗粒。

### 1.3　悬浮液粘性和导热系数测量方法

本次实验采用了英国 Malvern公司生产的 Bohlin CVO转矩流变仪测量了 NMPCM悬浮液在不同温度和浓度下的粘度变化情况。实验测量过程中,采用了 Mooney测量系统来测量纳米流体的粘度。该仪器用于温度控制装置,可用于测量不同温度条件下的纳米流体的粘度变化情况,同时采用了 Mooney测量系统的流变仪可以较为精确地测量出例如水等粘度较低的液体。采用粘度为 1 Pa·s的标准油校和流变仪的精度,结果显示系统误差小于 5%,满足实验测量的要求。

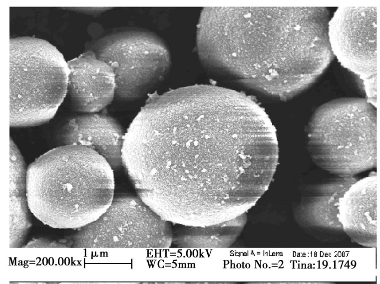


图 4　NMPCM悬浮液中的颗粒分布

本研究中还利用 KD2热物性仪(Labcell Ltd, UK)测量水和悬浮液的导热系数,KD2的测量原理是热线法,其原理是测量埋设在试样中的线形热源在一定时间内的温升。通过焊接在热线中点的热电偶测量热线温度随时间的变化,该线的温度变化即是被测材料导热系数的函数。该热物性仪的测量精度为 5%。

## 2　结果和讨论

### 2.1　悬浮液粘性

首先测量了不同浓度下相变悬浮液的粘性,如图 5所示,除了在起始段,相变悬浮液的粘性系数不随剪切力的变化而变化,说明在本研究条件下,体积浓度为 5%和 10%的两种相变悬浮液均可以被视为牛顿流体。

图 6为相变悬浮液和水的相对粘性系数,同时给出的还有 Vand模型对悬浮液粘度的预测结果[12]:

$$\mu_{MPCM}=\mu_w(1-c-1.16c^2)^{-2.5} \tag{1}$$

如图 6所示,当体积浓度小于 2.5%时,测量结果与 Vand模型的预测结果符合的较好,但当浓度进一步提高时,悬浮液的粘度非线性增加,比模型的预测结果高出许多,这是因为 Vand模型忽略了颗粒间的相互作用,不适用于浓度高的悬浮液。

为了研究纳米颗粒对相变悬浮液粘性的影响,

将 NMPCM悬浮液中的相变颗粒体积浓度固定为 10%，只改变纳米颗粒的浓度。如图 7所示，两种浓度下的 NMPCM悬浮液粘度基本不随剪切应力的变化而变化，因此，本研究的浓度范围内，NMPCM悬浮液可以被视为牛顿流体。

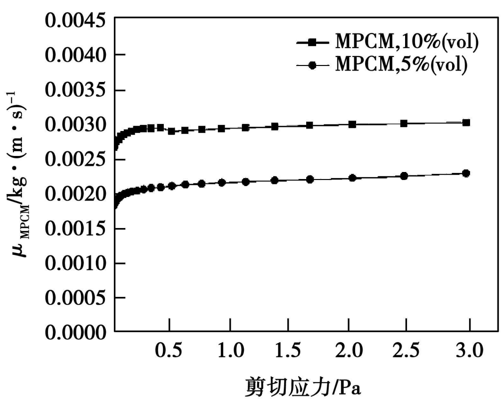


图 5　相变悬浮液粘性系数随剪切力的变化，15℃

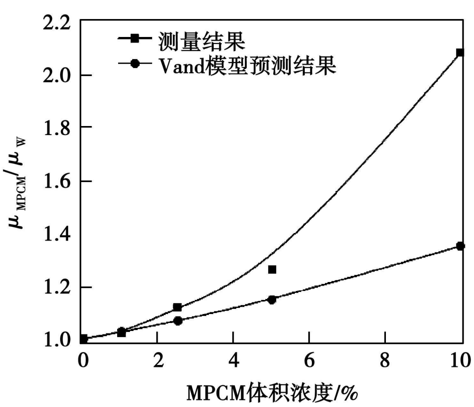


图 6　相对粘性系数随体积浓度的变化，15℃

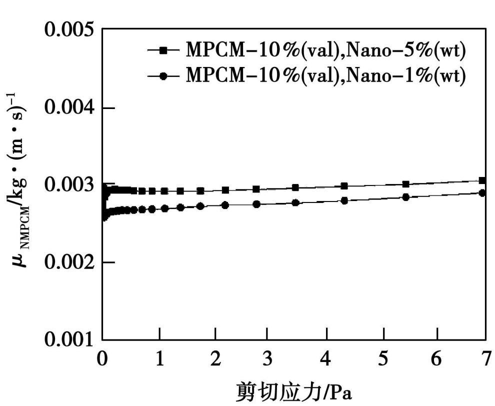


图 7　NMPCM悬浮液粘性随剪切力的变化，15℃

图 8为纳米颗粒浓度对 NMPCM悬浮液粘性的影响，其中 $\mu_{MPCM}$为体积浓度 10%的相变悬浮液粘性系数。由图可见，随着纳米颗粒浓度的增加，NMPCM悬浮液的粘性系数以非线性方式逐渐增加，但增长幅度并不大，当纳米颗粒浓度为 5%时，NMPCM悬浮液粘度比体积浓度 10%的相变悬浮液高出约 23%。图 9为纳米流体的粘度随纳米颗粒浓度的变化情况，可以把它理解为纳米颗粒浓度对蒸馏水粘度的影响。从图中可以看出，随着纳米颗粒质量浓度的增加，纳米流体的粘度逐渐增加。比较图 8和图 9可以发现，同质量浓度下，纳米颗粒对体积浓度为 10%的相变悬浮液粘度的增加幅度要高于对蒸馏水粘度的增加幅度，其具体机理还需要进一步研究，一个可能的原因是纳米颗粒和相变微胶囊两种颗粒相互作用的结果。

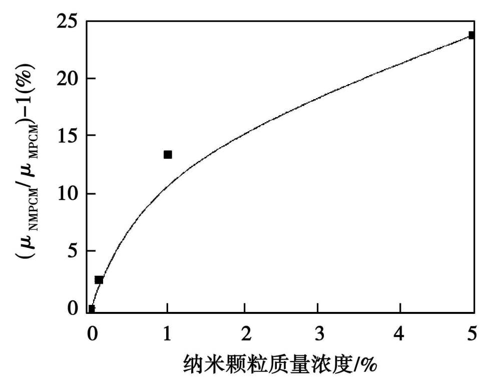


图 8　纳米颗粒对 NMPCM悬浮液粘性影响，15℃

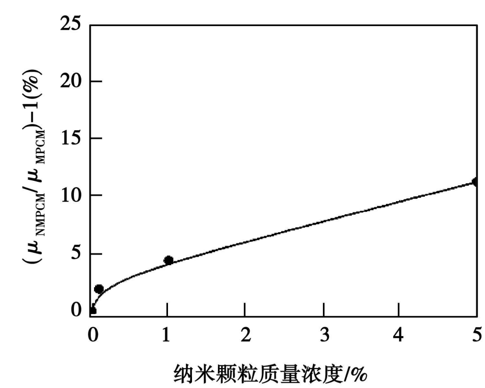


图 9　纳米颗粒对蒸馏水粘性影响，15℃

## 2.2　悬浮液导热系数

本研究首先测量了不同浓度下相变悬浮液的导热系数，如图 10所示。图中同时给出了 H-C模型的预测结果[13]：

$$k_{MPCM}=k_w\left[\frac{k_p+(n-1)k_w-(n-1)\phi(k_w-k_p)}{k_p+(n-1)k_w+\phi(k_w-k_p)}\right] \qquad (2)$$

式中: $k_{MPCM}$—相变悬浮液的导热系数; $k_p$和 $k_w$—相变颗粒和水的导热系数; $n = 3/\psi$是形状系数, 当颗粒是球形时, $\psi = 1$。

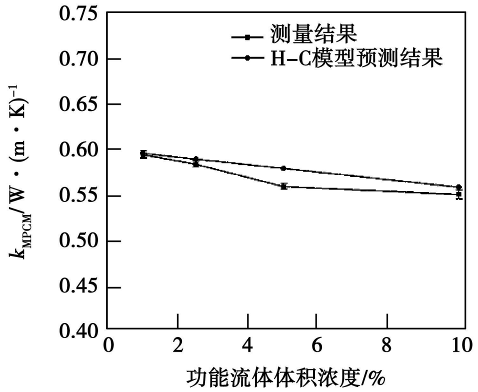


图 10　相变悬浮液导热系数随体积浓度的变化, 15℃

如图 10所示, 测量结果与 H-C模型的预测结果符合的较好。随着体积浓度的提高, 相变悬浮液的导热系数持续下降, 这对相变悬浮液强化传热效果是很不利的。以相变悬浮液在壁面施加热流的管道内流动为例, 壁面附近的流场由于温度升高较快, 相变悬浮液迅速熔化, 但由于相变悬浮液导热系数较低, 热量由管壁向流场内部传递较慢, 致使流场内部的很多相变颗粒还没有熔化就流出了管道, 没有起到强化传热的效果。由图 10还可知, 如果不希望导热系数降低过多, 浓度就不能太高, 但低浓度的相变悬浮液潜热量较低, 强化传热的能力有限, 如何在不损失潜热量的前提下提高相变悬浮液的导热系数, 对相变悬浮液的实际应用是至关重要。

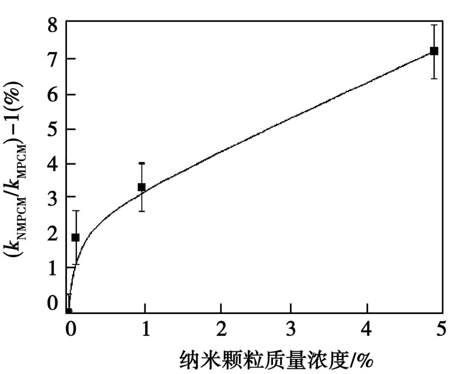


图 11　纳米颗粒对相变悬浮液导热系数的提高

与研究粘性时的处理方法类似, NMPCM悬浮液中的相变颗粒体积浓度固定在 10%, 通过改变悬浮液中纳米颗粒的质量浓度来研究纳米颗粒的加入对相变悬浮液导热系数的影响幅度。如图 11所示, 纳米颗粒的加入显著地提高了相变悬浮液的导热系数, 并且随着纳米颗粒浓度的增加, 导热系数提高的幅度也越高, 当纳米质量浓度达到 5%时, 相变悬浮液的导热系数提高幅度达到 7.3%。

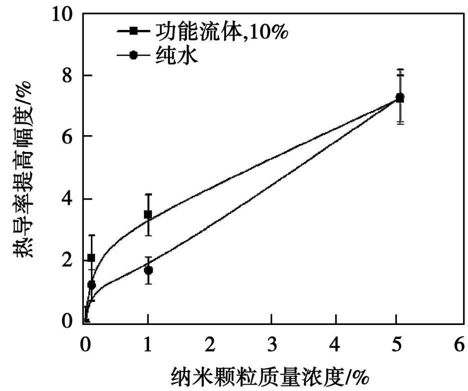


图 12　相变悬浮液和水导热系数提高幅度对比

为了更深入地理解纳米颗粒对相变悬浮液导热系数的影响幅度, 将纳米颗粒对纯水和相变悬浮液两种工质的导热系数提高幅度进行了对比, 如图 12所示。当纳米颗粒浓度较低时, 纳米颗粒对相变悬浮液导热系数的提高幅度要明显高于对纯水的提高幅度, 原因是纯水的导热系数要高于浓度 10%的相变悬浮液, 根据以往的研究结果[10~11], 纳米颗粒对低导热系数基液的导热系数提高幅度要更高。而随着纳米颗粒浓度的进一步提高, 这两种提高幅度越来越接近, 当纳米颗粒浓度达到 5%时, 两种提高幅度几乎一致。这种现象的具体原因还有待于进一步研究, 一个可能的原因是纳米颗粒与相变颗粒之间的相互作用。

## 2.3　NMPCM悬浮液作为传热工质的优势

在分析了 NMPCM悬浮液的粘性和导热系数特性后, 可以总结出与单纯的相变悬浮液相比, NMPCM悬浮液作为传热工质的优势:

(1) 纳米颗粒的加入提高了相变悬浮液的导热系数而粘度的提高幅度有限, 即使不考虑相变效果, 相变悬浮液的传热能力也会因此而提高。

(2) 导热系数的提高可以使热量更快地由壁面传递到流场内部, 相变颗粒熔化的更快更充分, 吸收潜热。

(3) 根据研究人员研究表明, 纳米颗粒对对流换热系数的提高幅度比导热系数的提高幅度更高, 因此在相变悬浮液中加入纳米颗粒, 可以从整体上提高相变悬浮液的对流换热系数, 这还需通过对流换热实验进一步研究。

## 3 结 论

本研究将纳米颗粒加入到相变悬浮液中得到一种新的传热工质，实验研究了这种悬浮液的粘性和导热系数特性，并得出如下结论：

（1）当纳米颗粒质量浓度不超过 5%时，NMPCM悬浮液可视为牛顿流体。

（2）悬浮液的粘性随纳米颗浓度的提高而提高，当纳米质量颗粒浓度为 5%时，相变悬浮液粘性提高约 23%。

（3）同质量浓度下，纳米颗粒对相变悬浮液粘度的提高幅度要大于对蒸馏水粘度的提高幅度。

（4）相变悬浮液导热系数随着纳米颗粒浓度的提高而提高。当纳米颗粒质量浓度为 5%时，相变悬浮液导热系数提高约 7%。

（5）当纳米颗粒浓度较低时，纳米颗粒对相变悬浮液导热系数的提高幅度要明显高于对纯水的提高幅度，而当纳米颗粒浓度达到 5%时，两种提高幅度趋于一致。

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新技术、新产品

# 先进的超级再热汽轮机

据《Kawasaki Technical Review》2008年 1月号报道，为下一代 LNG(液化天然气)运输船推进装置研制了先进的超级再热(URA)汽轮机，该型汽轮机显著地提高效率，具有可靠性、可维护性。

利用 FEM(有限元法)对现有的 UR型再热汽轮机的热力特性数据进行了分析，并针对 URA型再热汽轮机做了改进。

证实了常规的 UR型汽轮机应用先进的减速齿轮技术也可用于 URA型再热汽轮机装置。

表列了 URA型(超级再热)、UR型(常规再热)和 UA型(无再热)汽轮机和减速齿轮箱主要特性，并对其进行比较分析。

给出了新的 URA型汽轮机的总布置图、高压和中压汽轮机的纵剖面图、低压汽轮机的纵剖面图、主蒸汽和再热蒸汽入口部分的结构图、利用有限元法分析的应力分布图和机匣的温度分布图。

（吉桂明 摘译）

the optimum pressure ratio of the gas turbine-based simple cycle. Hence, the chemical recuperative cycle can be regarded as one not restricted by the pressure ratio. The depth of the fuel-steam conversion in the chemical recuperative cycle is relatively heavily affected by the exhaust gas temperature. The lower the exhaust gas temperature, the less the growth rate of the heating value of the fuel. Key words: gas turbine, chemical recuperative cycle, performance analysis, entropy-temperature diagram, thermal efficiency, pressure ratio

水和水蒸气热力性质 IAPWS-IF97计算模型分析及算法设计 = An Analysis of IAPWS-IF97 Formulae-based Model for Calculating Water and Steam Thermodynamic Properties and Its Algorithm Design [刊, 汉] / ZHOU Yan-ming, LI Ji-geng, LIU Huan-bin, ZHANG Ding-hua (National Key Laboratory on Pulp Preparation and Papermaking Engineering, South China University of Science and Technology, Guangzhou, China, Post Code: 510641) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). —166~171

By adopting an object-oriented method, implemented was the latest industrial formulae-based IAPWS-IF97 (2007. 8 Revision) for calculating water and steam thermodynamic properties. The calculation models for various zones were analyzed in detail with their corresponding implementation algorithms being designed. The basic equations, derivative equations, calculation formulae in various attributes and reversely derived equations for all the zones were implemented. The supplementary equation, B23 equation and B2bc equation for the metastable steam regions in two zones were also executed. The authors have presented the regional differentiated algorithm, sub-regional differentiated algorithm in two zones and Newton iterative algorithm in three zones to determine the density ρ from pressure P and temperature T. They have also described in detail the latest IAPWS-IF97 implementation method, matters meriting attention and relevant derivative processes, and supplemented the verification values of the computer program for specific heat capacity of equicapacitance $c_v$, thus enhancing the consistency of B23 with boundary $T_s$ (P) as well as that of B2bc with boundary $P_s$ (T). The application of the above in the papermaking industry indicates that the implemented method enjoys such a variety of merits as comprehensiveness, accuracy, speedy and automatic testing etc. Key words: IAPWS-IF97, water and steam, thermodynamic properties, industrial formulae, papermaking industry

$TiO_2$纳米颗粒对相变悬浮液流变和导热系数特性影响研究 = Study of the Influence of $TiO_2$ Nano-particles on the Rheology and Heat Conduction Coefficient Characteristics of a Phase-change Suspension [刊, 汉] / JIN Jian, LU Pei-qing, LIN Gui-ping (College of Aeronautical Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100191), DING Yu-long (College of Particle Science and Engineering, University of Leeds, Leeds, UK, Post Code: LS9 JT) // Journal of Engineering for Thermal Energy & Power. — 2010, 25(2). —172~176

By using an experimental method, studied were the viscosity and heat conduction coefficient of a phase-change suspension after it has been mixed with $TiO_2$ nano-particles. The research results show that when the concentration of the nano-particles does not exceed 5%, the suspension can still be viewed as a Newtonian fluid and its viscosity will increase nonlinearly with an increase of the concentration of the nano-particles. When the concentration of the mass nano-particles equals to 5%, the viscosity of the phase-change suspension will rise by about 23%. The addition of the nano-particles is capable of significantly improving the heat conduction coefficient of the suspension in question. When the concentration of the nano-particles is 5%, the heat conduction coefficient of the phase-change suspension will increase by about 7%. When the concentration of the nano-particles is relatively low, the growth margin of the heat conduction coefficient of the phase-change suspension caused by the nano-particles will be higher than that of the water. The authors have analyzed from different perspectives the advantages of using the new type of

suspension to serve as a heat transfer working medium. Key words: phase-change microcapsule, nano-particle, nano-fluid, Newtonian fluid, latent heat

汽水分离器分离效率的冷态实验研究 = Cold-state Experimental Study of the Separation Efficiency of a Steam-water Separator [刊, 汉] / XIAO Li-chun, DING Zhi-jiang (College of Environment and Chemical Engineering, Yanshan University, Qinhuangdao, China, Post Code: 066004), LI Qiang, YANG Jing-fei (College of Material Science and Engineering, Hebei University of Science and Technology, Shijiazhuang, China, Post Code: 050018) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (2). —177 ~ 179

Studied was a novel high-efficiency steam-water separation device destined for nuclear power stations. In the light of the complexity of the two-phase flow in a wave-shaped plate type steam-water separator, a cold-state experiment was performed under the condition of changing structural parameters and working states. The separation efficiency was measured by using a glass fiber filtration method. It has been found that the efficiency of a wave-shaped plate steam-water separator with water collection hooks is far higher than that of a separator without the hooks. To lengthen the pleated edge has little influence on efficiency. To enhance the separation efficiency, the inflexion angle should be set at 54 degrees and the plate spacing, at 20 mm. The critical value of the gas flow velocity is 5 m/s. When the flow speed is in excess of the critical value, the water film will rupture, a secondary entrainment or carryover will increase significantly and the dewatering efficiency will drop. The optimum structural parameters obtained from an analysis of the test data can be used for guiding the design of the device under discussion. Key words: steam-water separator, separation efficiency, wavy plate, structural parameter, critical wind speed

直接空冷枝状排汽管道系统内导流装置的优化设计 = Optimized Design of the Flow Guiding Device for a Direct Air-cooled Branch-shaped Exhaust-steam Piping System [刊, 汉] / SHI Lei, WANG Jin (College of Civil Engineering, Beijing Jiaotong University, Beijing, China, Post Code: 100044), SHI Cheng (China Electric Power Engineering Consultant Group Corporation, Beijing, China, Post Code: 100011), LIU Guo-yin (Jiangsu Shuangliang Air-connditioning Equipment Co. Ltd., Jiangyin, China, 214444) // Journal of Engineering for Thermal Energy & Power. — 2010, 25 (2). —180 ~ 183

Studied was an invention patent of German GEA Energyietechnik Gmbh-a direct air-cooled branch-shaped exhaust steam piping system, and established was a mathematical model for the wet steam two-phase flow and heat transfer in a direct air-cooled exhaust steam pipeline of a 2×600 MW unit. By employing the numerical heat transfer software Fluent, the authors have conducted a numerical simulation of the exhaust steam situation under typical steam turbine operating conditions. Through a simulation, they have also analyzed and studied the wet steam velocity field, temperature field and two-phase field in a two-dimensional pipeline. The simulation results show that the flow division method according to the simple geometrical principles proposed in the invention patent is incapable of realizing a uniform distribution of the exhaust steam. In view of this, depending on the direct air-cooled branch-shaped piping system in different forms, a detailed optimized design should be conducted. Moreover, the basic design principles of the flow guiding device for the system in question were also given. Key words: direct air-cooled system, numerical simulation, branch shape, exhaust steam pipe, optimized design

增压锅炉汽包低周疲劳寿命计算方法研究 = Study of the Methods for Calculating the Low-cycle Fatigue Life of a Supercharged Boiler Drum [刊, 汉] / ZHENG Xin-wei (College of Power and Energy Source Engineering, Harbin Engineering University, Harbin, China, Post Code: 150001), SUN Yu (Offshore Oil Engineering