

一种多股流换热器综合性能优化设计方法

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摘 要: 在综合考虑了体积、重量和阻力等因素的基础上, 对多股流换热器进行通道排列和优化设计, 并运用无量纲分析法, 自定义了 syn 因子、 syn 线等用以评价换热器综合性能的指标。详细分析了应用 syn 因子综合优化翅片结构的过程, 与实际的设计结果比较表明: 该方法适用于多股流换热器的综合性能优化设计。

关 键 词: 多股流换热器; 无量纲分析法; syn 因子

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1 前 言

多股流板翅式换热器作为紧凑式换热器的一种, 由于其具有体积小、重量轻、效率高等突出优点, 越来越多地应用于空气分离、石油化工、动力机械、宇宙航行等工业部门, 被认为是最有发展前途的新型热交换设备之一。板翅式换热器的成本高达 17 500 美元/ m^3 , 故其优化设计显得尤其重要^[1,4]。由于国内铝材的价格约为 15~20 万元/t, 因此用减轻重量的方法来减少成本和初投资。

在以往文献的设计中, 往往只考虑换热性能与阻力作为优化条件, 而本文在此基础上又综合考虑了体积与重量的因素。以各种流体的阻力、体积与重量作为优化目标函数, 利用编制的多股流板翅式换热器的设计程序, 改变翅高与翅片间距, 计算了 50 多个工况, 分别指出了体积、重量、阻力最佳时段的翅片高度。本文提出了无量纲分析法, 借助于无量纲参数把数量级不同的体积、重量、各流体的阻力变化趋势以及自定义的 syn 线综合到一张图上, 便于分析比较不同性能指标随翅片结构的变化规律以及 syn 因子的变化规律, 与国内某空分厂的设计结果比较表明, 此方法是可行的。

2 理论模型

本文以空气分离设备的切换式换热器作为研究对象, 一般采用锯齿形翅片, 既强化气流换热, 又便

于水分和二氧化碳的析出和清除。

石油化工、气体分离低温技术中大量应用的多股流板翅式换热器多属于一股热流体与多股冷流体同时换热的情况, 当然也有热、冷流体同时均为多股的, 但实用上以前者为多^[2]。本文参考了文献^[2]综合法的基本思想, 按给热、吸热分别综合, 使它成为相当的两股流体, 即热流体给热, 冷流体吸热, 从而把多股流换热问题简化成两股流换热来进行处理。综合法在国内的空分设备行业厂一直沿用, 国外的某些专业设备厂也仍然在使用。

传热计算后即可进行长度的计算。综合以后相当两股流的热导 KA ^[2] 为:

$$KA = h_h A_h \eta_h \times \frac{\sum_{i=1}^{i=nc} h_i A_i \eta_i}{h_h A_h \eta_h + \sum_{i=1}^{i=nc} h_i A_i \eta_i} \quad (1)$$

式中: h — 换热系数, $W/(m^2 \cdot K)$; A — 换热器各股流体 1 m 长的换热面积, m^2 ; η — 翅片表面总效率; 下标 h — 热流体; nc — 冷流体的数目。

平均温差 ΔT 可由冷热流体进出口温度的加权平均数来确定^[3]:

$$\Delta T_{he} = \frac{\sum_{i=1}^{i=nh} \dot{m}_i \cdot c_{p_i} \cdot T_{i, in}}{\sum_{i=1}^{i=nh} \dot{m}_i \cdot c_{p_i}} - \frac{\sum_{i=1}^{i=nc} \dot{m}_i \cdot c_{p_i} \cdot T_{i, out}}{\sum_{i=1}^{i=nc} \dot{m}_i \cdot c_{p_i}} \quad (2)$$

$$\Delta T_{ce} = \frac{\sum_{i=1}^{i=nh} \dot{m}_i \cdot c_{p_i} \cdot T_{i, out}}{\sum_{i=1}^{i=nh} \dot{m}_i \cdot c_{p_i}} - \frac{\sum_{i=1}^{i=nc} \dot{m}_i \cdot c_{p_i} \cdot T_{i, in}}{\sum_{i=1}^{i=nc} \dot{m}_i \cdot c_{p_i}} \quad (3)$$

$$\Delta T = (\Delta T_{he} + \Delta T_{ce})/2 \quad (4)$$

综合以后相当两股流的换热器理论长度为:

$$L = Q/(KA \cdot \Delta T) \quad (5)$$

式中: he — 热端; ce — 冷端; nh — 热流体的数目; Q — 总热负荷, kW 。

在综合法中尚要分别计算各股冷气流与对应的

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按传热面积比例分配的热气流之间进行传热所具有的热导 KA_{c-h} ^[1]、所需的通道长度 L_c 及综合与分解计算所得长度偏差 ΔE ，此过程被称为长度的校核计算。

$$KA_{c-h} = \frac{h_c A_c \eta_c h_h A_h \eta_h (A_c / \sum_{i=1}^{i=n} A_i)}{h_c A_c \eta_c + h_h A_h \eta_h (A_c / \sum_{i=1}^{i=n} A_i)} \quad (6)$$

$$L_c = Qc / (KA_{c-h} \times \Delta T) \quad (7)$$

$$\Delta E = (L - L_c) / L \quad (8)$$

式中：下标 c —冷流体

一般希望 ΔE 在 5% ~ 10%。

最后进行压降的计算，芯体的阻力 ΔP 可表示为：

$$\Delta P = 4f \times L \cdot G^2 / (d_s \cdot 2\rho) \quad (9)$$

式中： G —质量流速， $kg / (m^2 \cdot s)$ ； d_s —当量直径， m ；

ρ —密度， kg / m^3 。

3 换热器综合性能的评价和设计分析

体积、重量和阻力均与翅片高度有关，但它们的数量级差别较大，把这些关系曲线作在同一张图上，不能反应出各自的变化趋势，所以本文提出了无量纲法。定义无量纲参数等于(实际数减最小值)除以(最大值减最小值)，即可获得各组数的 0 ~ 1 区间的无量纲结果。这样就能在同一张图上表示出各种变量随翅片参数的变化关系，以便于分析比较。当考虑换热器的综合性能时，这些参数无法都取得最佳值，而实际换热器的设计亦如此，只能获得各项指标折衷的设计结果。因此，本文建立了用以评价换热器的综合性能的评价参数—— syn 因子(综合性能评价因子，英文“synthesis”的缩写)，表示为 syn 等于体积加重量加氧气阻力加空气阻力，分子的各项均为无量纲数，所以 syn 因子也是一个无量纲数。在式中， syn 因子是把体积、重量、阻力放在同等重要的位置，即所取权重相等。

以某空分厂的 4 股流板翅式换热器为例，流体分别为空气、氧气、氮气、污氮。给出各股流体的冷端温度、热端温度、压力、热负荷、流量和标况密度，如表 1 所示。

表 1 工况设计参数

	冷端温 度/K	热端温 度/K	压力 /kPa	热负荷 /kW	流量 /m ³ ·s ⁻¹	标况密 度/kg·m ⁻³
氧气	129.15	290.15	149	8.8016	0.04188	1.4289
污氮	129.15	290.15	134.47	10.7054	0.05145	1.28
空气	142.35	293.15	1294	49.6182	0.23644	1.2928
氮气	129.15	290.15	134	30.1112	0.14312	1.25673

3.1 冷通道翅高不变，热通道翅高变化以及等权重的计算

3.1.1 设定冷通道翅片高度为 8.5 mm，热通道翅高变化范围为 3.0 ~ 9.5 mm，翅片间距均为 1.4 mm，翅厚为 0.2 mm。计算结果经无量纲分析法处理后，如图 1 所示。(由于冷通道阻力变化趋势一致，本图只给出了氧的阻力)。从图中可看出最佳点应在空气翅高为 5.0 ~ 6.0 mm 区间内。在翅高为 3.0 ~ 5.0 mm 的区间，体积虽然很小，但阻力和重量却很大，故不可取。在 6.0 ~ 9.5 mm 区间内，虽然冷热通道的阻力急剧下降，体积与重量却也随着骤然上升。对阻力要求较高的企业可采用这一区段。

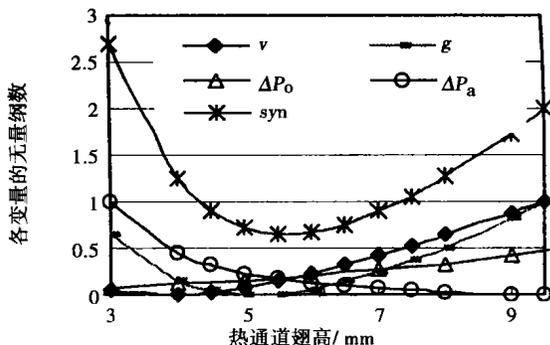


图 1 冷通道翅高为 8.5 mm，体积、重量、阻力与热通道翅高的关系

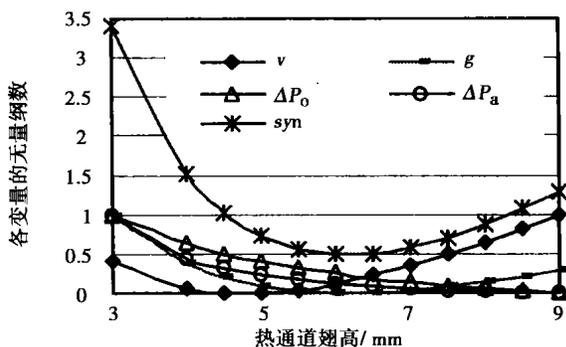


图 2 冷通道翅高为 9.5 mm，体积、重量、阻力与热通道翅高的关系

3.1.2 设定冷通道翅高为 9.5 mm，热通道翅高变化范围为 3.0 ~ 9.0 mm，翅片间距均为 1.4 mm，翅厚为 0.2 mm，计算结果如图 2 所示。可知最佳点应在 6.0 ~ 7.0 mm 区间内。在 4.0 ~ 6.0 mm 区间内，体积虽有最小值，但阻力很大。在 7.0 ~ 9.0 mm 区间内，阻力下降趋势缓慢，体积与重量却又急剧上升。图示说明： v —体积； g —重量； ΔP_o —氧阻力； ΔP_a —空气阻力； syn —综合性能评价因子线； $gsyn$ —重量

权重为 75% 时的 syn 线; $\Delta P_{o,syn}$ —氧气阻力权重为 45% 时的 syn 线。

3.1.3 设定冷通道翅高为 12.0 mm, 间距 1.4 mm, 翅厚 0.3 mm; 热通道翅高变化范围为 3.0 ~ 11.5 mm, 间距为 1.4 mm, 翅厚 0.2 mm, 计算结果如图 3 所示。最佳点应在 6.5 ~ 7.5 mm 区间内。

3.1.4 设定冷热通道的翅高相等, 间距均为 1.4 mm, 翅厚均为 0.2 mm, 计算结果如图 4 所示。四者的交点应为最佳点: 翅高为 5.2 mm。

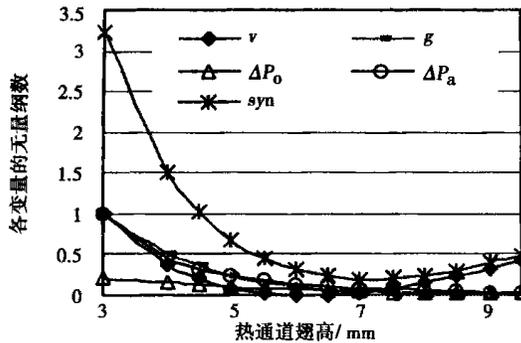


图 3 冷通道翅高为 12.0 mm, 体积、重量、阻力与热通道翅高的关系

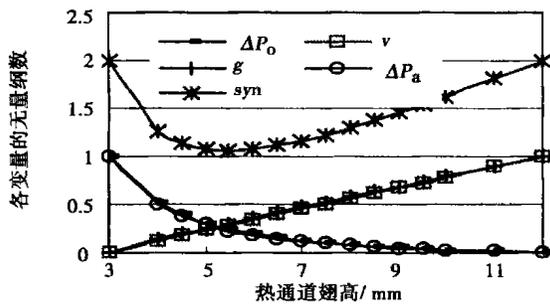


图 4 冷通道翅高相等时, 体积、重量、阻力与热通道翅高的关系

在每种最佳点范围内选出几个点, 综合进行比较, 如表 2 所示。从表中容易看出冷通道翅高为 9.5 mm, 热通道翅高为 6.5 mm 时, 阻力与体积、重量匹配较好, 可认为是最佳点。此外, syn 线较好地反应了最佳点的位置, 由图 1 ~ 图 4 可知 syn 线的极小值恰好在最佳点范围内, 因此可直接从 syn 线入手进行设计。国内某空分厂的翅片设计参数与此吻合得很好: 冷通道翅高为 9.5 mm, 空气通道为 6.5 mm, 在 3.1.2 节中的最佳区域内。

3.2 权重不同时的计算

前面所建立的 syn 综合优化因子是按照等权重

来定义的, 当然各个企业也可根据自己不同的需要取不同的权重。以 3.1.1 为例, 假定重量权重占 75%, 其它三项共占 25% (平均分配), 作图得出线 $gsyn$, 如图 5 所示。从图中能明显看出: 与 syn 线相比, $gsyn$ 线的极小点左移, 即热通道的翅片高度减小, 也就是说, 若对换热器的重量要求较高, 可选取翅片高度较小的翅片 (可找出最佳点)。再假定氧气阻力权重占 45%, 其他三项共占 55% (平均分配), 作图得出 ΔP_{osyn} 线, 如图 6 所示。与 syn 线相比, ΔP_{osyn} 线的极小点右移, 若对换热器的氧通道阻力要求较高, 可选取翅片高度稍大的翅片。这样可得翅片高度的精确值, 从而对设计者有指导意义。

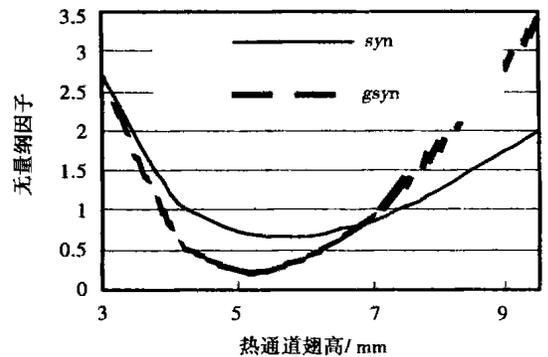


图 5 重量权重为 75% 与等权重时的比较

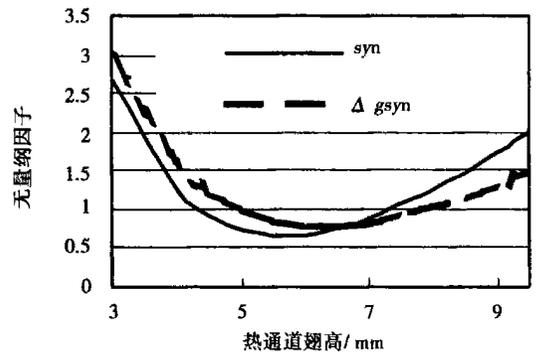


图 6 氧气阻力权重为 45% 与等权重时的比较

表 2 工况最佳点比较

冷通道翅高/mm	热通道翅高/mm	体积 /m ³	重量 /kg	氧气阻力/Pa	空气阻力/Pa
8.5	5.0	0.194 005	177.992	1 453.007	1 230.741
	5.5	0.195 544	178.067	1 436.581	998.243
	6.0	0.197 390	178.450	1 422.993	828.373
9.5	6.0	0.217 23	191.167	1 206.205	848.105
	6.5	0.218 628	191.196	1 193.178	715.054
	7.0	0.220 318	191.505	1 182.159	612.588
12.0	6.5	0.252 890	243.537	1 047.091	706.190
	7.0	0.253 457	242.609	1 034.318	603.185
	7.5	0.254 396	242.070	1 023.402	522.394
5.2	5.2	0.135 390	140.295	3 322.031	1 053.660

4 结 论

通过采用无量纲分析法对多股流板翅式换热器优化设计的研究, 得出如下结论:

- (1) 体积、重量与阻力有制约关系, 要优化设计只能找出一个综合各种制约参数的最佳区域;
- (2) 对多股流板翅式换热器的设计来说, 无量纲分析法是一个非常有效的方法;
- (3) *syn* 线真实地反应了体积、重量、阻力的变化情况。计算后, 工程设计人员可直接从 *syn* 线入手, 找出翅片的最佳参数。若对体积、重量、阻力的

侧重点不同, 根据所取权重可分别作出各自的线, 找出最佳设计区域。

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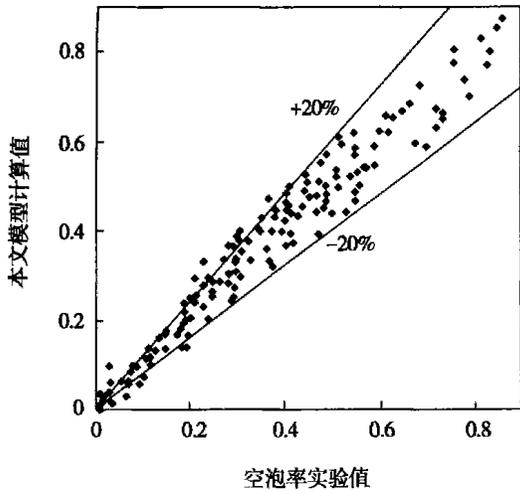


图 3 分布拟合模型与较低流速数据比较

分布拟合模型与表 1 中所有较高流速实验数据 ($G > 900 \text{ kg}/(\text{m}^2 \cdot \text{s})$) 的比较如图 4 所示, 可见对于较高流速工况 ($G > 900 \text{ kg}/(\text{m}^2 \cdot \text{s})$), 本文模型虽然仍可得出比较满意的预测结果, 但其预测精度较低流速工况明显降低。

5 结 语

基于本文作者于文献[1] 提出的低流速过冷沸腾 NVG 点理论模型, 进一步建立了计算低流速过冷沸腾空泡率的分布拟合模型。通过与现有实验数据的比较表明, 该模型在低流速过冷沸腾工况可得出非常满意的空泡率计算结果。

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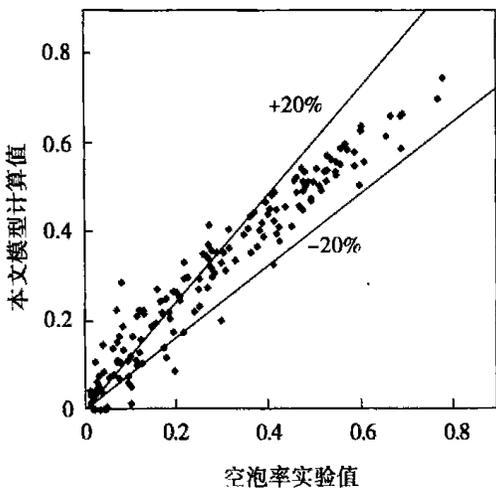


图 4 分布拟合模型与较高流速数据比较

film, compact heat exchanger

一种多孔介质蒸发冷却中冷器性能的初步研究 = **A Preliminary Study of the Performance of a Porous-medium Evaporative Cooling-based Intercooler** [刊, 汉] / ZHANG Zhen-yi, ZHANG Yan, SUN Yu-feng (College of Power and Nuclear Energy Engineering under the Harbin Engineering University, Harbin, China, Post Code: 150001) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 163 ~ 166

The theory and construction of an evaporation-cooled intercooler is briefly described. By way of wind tunnel tests the resistance and temperature-reduction characteristics of various packings were verified, resulting in the selection of proper packing media. It is shown that the evaporation-cooled intercooler is simple in theory and can be installed at the inlet of a diesel and gas turbine and employed on a ICR (intercooled recuperative) marine gas turbine. It is feasible to use the intercooler under discussion to replace an originally installed intercooler. **Key words:** evaporative cooling, intercooler, packing

基于复合进化算法和 Navier—Stokes 方程求解技术的透平叶栅气动优化设计 = **Optimized Aerodynamic Design of Turbine Cascades Based on Composite Evolutionary Algorithms and Navier-Stokes Equation Solution Techniques** [刊, 汉] / LI Jun, REN Bin, FENG Zhen-ping (College of Energy & Power Engineering and Institute of Turbomachinery under the Xi'an Jiaotong University, Xi'an, China, Post Code: 710049) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 167 ~ 170

The optimized aerodynamic design of turbine cascades is presented, which has been based on composite evolutionary algorithms and Navier-Stokes equation solution techniques. By combining evolutionary algorithms with a Simplex method the resulting composite evolutionary algorithms can enhance the search efficiency of evolutionary hereditary algorithms through a reform of the worst individuals in a population by using the Simplex method. The design objective of turbine cascade aerodynamic optimization is to minimize the total pressure loss. The coordinates of the control points of Bezier curves for the cascade profile parametrization serve as the optimized design variables. Reynolds-averaged Navier-Stokes equation solution techniques were used to calculate the total pressure loss. Baldwin-Lomax algebraic turbulent model is used as a turbulent model. The optimized design has reduced the total pressure loss of the cascades by 20%. The design results demonstrate that the optimization techniques used by the authors for the turbine-cascade aerodynamic design proved to be an effective approach. **Key words:** composite hereditary algorithm, turbine cascade, optimization, design

一种多股流换热器综合性能优化设计方法 = **Comprehensive-performance Optimization Design Method for Multi-stream Heat Exchangers** [刊, 汉] / ZHAO Yong-qin, CUI Guo-min, LU Hong-bo, LI Mei-ling (Research Institute of Thermal Engineering under the Shanghai University of Science and Technology, Shanghai, China, Post Code: 200093) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 171 ~ 174

On the basis of a comprehensive consideration of such factors as volume, weight and resistance, etc a flow-channel layout and an optimized design were carried out for a multi-stream heat exchanger. Moreover, a dimensionless analytical method is applied to define a synthesis (syn) factor and synthesis line, etc in order to evaluate the comprehensive performance of the heat exchanger. A detailed analysis is performed of the process of fin-structure comprehensive optimization by making use of the synthesis factor. A comparison of the analysis results with design ones indicates that the method under discussion is suitable for the comprehensive-performance optimization design of the multi-stream heat exchangers. **Key words:**

multi-stream heat exchanger, dimensionless analytical method, synthesis factor

叶片可靠性预测的非线性振荡低网格边界元法 = **Nonlinear-oscillating Meshless Boundary Element Method for the Prediction of Blade Reliability** [刊, 汉] / YANG Jian (Research Institute of Chemical Machinery under the Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 175 ~ 178

On the basis of a nonlinear fluid vibration-excitation theory a direct solution scheme for boundary integral equations of fluid structure coupling analysis has been set up to predict the fluid-excited vibration reliability of turbomachine blades. By using the linearization treatment of equivalent mean values and deviations a reliability index is evaluated, and a nonlinear meshless boundary element method proposed to analyze the reliability of blades. The results of numerical calculations indicate that the proposed method can be employed to realize a speedy and effective prediction of blade performance and to conduct an optimized probability design for a new type of turbomachinery. **Key words:** rotating machine, blade, reliability prediction, boundary element method

基于 BP 神经网络的汽轮机排汽焓在线计算方法 = **On-line Computation Method for Steam Turbine Exhaust Enthalpy Based on BP Neural Network** [刊, 汉] / GUO Jiang-long, ZHANG Shu-fang, CHEN Hai-ping (Power Engineering Department, North China University of Electric Power, Baoding, China, Post Code: 071003) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 179 ~ 181

The steam exhaust point of a steam turbine is located in a wet steam zone. Due to a lack of steam-wetness measuring instruments on-site it is difficult to determine directly the enthalpy of turbine exhaust steam. The calculation of this enthalpy has long been one of the difficult issues in the on-line analysis and diagnosis of thermal economics of a thermal power plant thermodynamic system. There exist numerous factors, which can affect the turbine exhaust enthalpy. The relationship between these factors and the exhaust steam enthalpy is a typical nonlinear one. With a NK200-12.7/535/535 type of air-cooled plant serving as an example the authors have recommended a method for setting up a model for calculating the turbine exhaust enthalpy by using a BP neural network. The method has been successfully put into use on an on-line diagnosis system of thermal economics for a power plant. **Key words:** turbine exhaust enthalpy, BP neural network, steam turbine, model

基于动态聚类算法的两相流流型识别方法研究 = **A Study of Two-phase Flow-pattern Identification Method Based on a Dynamic Clustering Algorithm** [刊, 汉] / JIA Zhi-hai, NIU Gang, WANG Jing (College of Mechanical and Power Engineering under the Shanghai Jiaotong University, Shanghai, China, Post Code: 200030) // Journal of Engineering for Thermal Energy & Power. — 2004, 19(2). — 182 ~ 185

Differential pressure signals of three flow patterns in a horizontal pipe, i. e., vapor/water two-phase laminar flow, agitation flow and elastic flow, have been collected. Through the use of a probability density function (PDF) method an analysis was conducted of the signal characteristics. The four eigen parameters reflecting PDF function variation, namely, peak number k_1 , maximum peak value k_2 , peak position k_3 and variance k_4 , have been defined. Then, by making use of a dynamic clustering algorithm a classification/identification was conducted for the above-mentioned three flow patterns. It can be shown that the use of PDF in conjunction with the dynamic clustering algorithm makes it possible to realize a speedy and accurate identification of the vapor/water two-phase flow pattern, testifying to the feasibility of the method under discussion. **Key words:** two-phase flow, flow pattern identification, probability density function, dynamic clustering