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凝汽器运行状态的物元模型及可拓评价方法

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摘 要: 在建立凝汽器运行状态评价指标的基础上, 针对评价指标的多样性及模糊性, 提出一种以物元模型和可拓关联函数为基础的凝汽器运行状态的可拓评价方法。基于可拓学中的物元理论, 建立起凝汽器运行状态评判的物元模型, 并利用一组可拓关联函数计算凝汽器运行的状态参数和状态等级之间的关联度, 由关联度的大小对凝汽器状态进行定性和定量评价, 最后通过实例验证了本方法的实用性。研究表明, 该方法能快速而有效地识别凝汽器运行状态, 为凝汽器运行状态的评价提供一种新的途径。

关 键 词: 凝汽器; 状态评价; 可拓学; 物元模型; 关联函数
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引 言

凝汽器是凝汽式汽轮机的主要辅助设备之一, 其运行性能对汽轮机组的安全经济运行有很大的影响。为保障机组的安全经济运行, 必须在日常运行中经常监督凝汽器运行状况, 综合评价其运行状态的优劣。传统的评价方法诸如建立在模糊集合论基础上的模糊综合评判法以其突出的特点广泛用于状态评价领域, 文献[1]也曾利用此方法对凝汽器运行状态进行了综合评价。由于描述凝汽器运行状态优劣的语言是模糊的, 而实际运行系统所测得的参数却是客观的, 利用实测的参数进行凝汽器运行状态的评价, 无法归纳出可用的数学公式, 因此存在着主客观相互矛盾的问题, 为了克服这一缺陷和使评价具有实用化, 提出以可拓理论评价凝汽器的运行状态。

可拓学相关理论是我国学者蔡文等人为解决主客观矛盾问题而于 1983 年所创立的理论[2~4]。可拓学的两大支柱是物元理论和可拓集合理论, 利用物元模型描述问题, 可以进行定量和定性的综合分析, 因此能够同时研究"量"和"质"两者对所描述问题的影响程度, 更能帮助研究者完整地认识系统特征的真实性, 已广泛应用于各种实际领域中。可拓评价方法是一种用形式化的模型研究事物拓展可能性规律的方法, 常用于处理多参数、混合度大的矛盾问题和不相容问题[3]。本文提出的凝汽器运行状态的可拓评价方法, 首先结合已有的凝汽器运行状态的评价指标和可拓理论, 建立凝汽器运行状态等级的物元模型, 再利用正规化关联函数计算出凝汽器运行状态各等级之间的关联度, 进而识别出凝汽器的运行状态, 最后利用实例验证这种方法的实用性。

1 可拓学基本理论

1.1 物元的基本理论

在可拓理论中, 物元包含了 3 个最基本的要素。设事物 R 的名称为 N, 特征为 C, 其关联于特征 C 的量值为 V, 则描述事物的基本元或物元为 $R=(N, C, V)$。

假设事物 $R=(N, C, V)$是一个具有多维的物元, 而事物有 n 个特征时, 可以用矩阵 $C=[c_1, c_2, \cdots, c_n]$ 代表, 其对应的量值分别用数值矩阵 $V=[v_1, v_2, \cdots, v_n]$ 代表, 则物元的表达式为[2~3]:

$$R=(N, C, V)=\begin{bmatrix} R_1 \\ R_2 \\ \vdots \\ R_n \end{bmatrix}=\begin{bmatrix} N, & c_1, & v_1 \\ & c_2, & v_2 \\ & \vdots & \vdots \\ & c_n & v_n \end{bmatrix} \quad (1)$$

1.2 可拓集合理论及其相关可拓函数

1.2.1 可拓集合的定义[2~3]

设论域 U 中任一元素 x 且 $x\in U$, 则有一实数 $k(x)\in(-\infty, \infty)$与之对应, 则可拓集合 A 定义为:

$$A=\{(x, y)\mid x\in U, y=k(x)\in(-\infty, \infty)\}$$

其中: $y=k(x)$—A 的关联函数。

可拓集合 A 在论域 U 中可表示成 $A=A^+\cup J_0\cup A^-$, 其中:

$A^+=\{(x, y)\mid x\in U, y=k(x)>0\}$—$A$ 的正域; $J_0=\{(x, y)\mid x\in U, y=k(x)=0\}$—$A$ 的零界;

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$A^{-}=\{(x, y)\mid x\in U, y=k(x)<0\}$ —A 的负域。

1.2.2　初等关联函数

描述经典集合的是特征函数, 其值域是{0, 1}, 描述模糊集合的是隶属函数, 其值域为[0, 1] 的实值函数, 而可拓集合是用关联函数来描述的。关联函数的取值范围是整个实数轴, 常用代数式子来描述可拓集合的关联函数, 使得解决不相容问题的过程定量化成为可能。根据实际应用问题的不同, 关联函数也有不同的形式。

设 $X_0=<a, b>$, $X=<a_p, b_p>$, $X_0\in X$ 且无公共端点, 则初等关联函数为:

$$k(x)=\frac{\rho(x, X_0)}{D(x, X_0, X)}$$

其点 x 与区间 X_0 的距定义为:

$$\rho(x, X_0)=\left|x-\frac{a+b}{2}\right|-\frac{b-a}{2}$$

其点 x 关于 X_0、X 的位值为:

$$D(x, X_0, X)=\begin{cases}\rho(x, X)-\rho(x, X_0) & x\notin X_0\\ -1 & x\in X_0\end{cases}$$

因此, 关联函数可以计算 x 点属于 X_0 的关联程度。

当 $k(x)\geqslant 0$, 表示 x 属于 X_0 的程度; $k(x)<0$ 时, 表示 x 不属于 X_0 的程度; $-1<k(x)<0$ 时, 表示如果状态发生改变时, x 有可能成为此集合的一部分[2~3]。

2　凝汽器运行状态的物元模型

2.1　凝汽器运行状态的评价等级及指标

文献[1] 中已归纳总结出用于评价凝汽器运行状态优劣的评价等级以及评价指标, 各指标的数值区间列入表 1。本文利用此评价指标体系和标准建立凝汽器运行状态的物元模型并对其进行可拓评价。

表 1　凝汽器运行状态多因素评价指标及标准

评价指标	评价等级			
	优	良	合格	差
凝汽器真空 X_{vac}	1.0~0.9	0.9~0.8	0.8~0.7	0.65~0
凝结水含氧量 C_a/μg	0~7	7~14	14~28	28~42
凝结水过冷度 δ_{sc}/℃	0~0.5	0.5~1.5	1.5~2.5	2.5~3.5
真空系统空气严密性, 真空下降速度 X_{ar}/Pa·min^{-1}	0~130	130~260	260~390	390~520
抽出的空气混和物的温度 X_{mtd}	0~0.6	0.6~0.8	0.8~1.0	1.0~1.2

注: 1. X_{vac}=(真空实测值—停机值)/(真空应达值—停机值)[5]; 2. 其余各评价指标的定义同文献[1]。

2.2　评价凝汽器运行状态的物元

2.2.1　凝汽器运行状态的物元模型

根据文献[1] 的研究结果, 可用下列 n 维物元来描述凝汽器运行状态的质量优劣:

$$R=(N, C, V)=\begin{bmatrix}N, & c_1, & v_1\\ & c_2, & v_2\\ & \vdots & \vdots\\ & c_n, & v_n\end{bmatrix},\ (n=5)\quad (2)$$

其中: R—凝汽器运行状态物元; N—凝汽器运行状态等级; C—凝汽器运行状态评价指标; V—凝汽器运行状态评价指标的量值。

2.2.2　确定凝汽器运行状态优劣等级的经典域

利用可拓理论及物元模型建模理论, 结合表 1 中各指标在各等级的数值区间, 分别建立凝汽器运行状态优劣等级的经典域, 其中:

$$R_1=\begin{bmatrix}\text{优}, & X_{vac}, & <0.9, 1.0>\\ & C_a, & <0, 7>\\ & \delta_{sc}, & <0, 0.5>\\ & X_{ar}, & <0, 130>\\ & X_{mtd}, & <0, 0.6>\end{bmatrix};$$

$$R_2=\begin{bmatrix}\text{良}, & X_{vac}, & <0.8, 0.9>\\ & C_a, & <7, 14>\\ & \delta_{sc}, & <0.5, 1.5>\\ & X_{ar}, & <130, 260>\\ & X_{mtd}, & <0.6, 0.8>\end{bmatrix};$$

$$R_3=\begin{bmatrix}\text{合格}, & X_{vac}, & <0.7, 0.8>\\ & C_a, & <14, 28>\\ & \delta_{sc}, & <1.5, 2.5>\\ & X_{ar}, & <260, 390>\\ & X_{mtd}, & <0.8, 1.0>\end{bmatrix};$$

$$R_4=\begin{bmatrix}\text{差}, & X_{vac}, & <0, 0.65>\\ & C_a, & <28, 42>\\ & \delta_{sc}, & <2.5, 3.5>\\ & X_{ar}, & <390, 520>\\ & X_{mtd}, & <1.0, 1.2>\end{bmatrix};$$

2.2.3　确定凝汽器运行状态的节域(特征物元)

在可拓学中, 建立了“节域”和“质度函数”两个概念。它们描述了客观事物由量变到质变的辩证规律。节域概念表达了事物的某性质对应的量值的范围, 当量值在节域的范围内变化时, 事物的性质就保持着它的稳定性。当事物某量值的变化超越节域时, 就会引起该性质向另一种性质的转化。利用可拓理论及物元模型建模理论, 根据“$X_0=<a, b>$,

$X=<a_p, b_p>$, $X_0 \in X$ 且无公共端点”这一要求, 结合表 1 中各指标从“优”到“差”的数值区间, 可建立凝汽器运行状态的节域, 即特征物元 R_p, 可表示为:

$$R_p=\begin{bmatrix} P, & X_{vac}, & <0, 1.0> \\ & C_a, & <0, 45> \\ & \delta_c, & <0, 5> \\ & X_{ar}, & <0, 540> \\ & X_{mtd}, & <0, 2> \end{bmatrix} \tag{3}$$

3 凝汽器运行状态的可拓评价方法及应用实例

3.1 可拓评价方法及流程

凝汽器运行状态的评判是一个较为复杂的问题, 利用物元分析方法可建立其运行状态好坏的状态评价模型, 并以定量的数值表示出评判结果, 可较完整地反映出凝汽器的运行状态, 并可利用计算机编制相应的专用程序, 完成对凝汽器的运行状态评价。基于物元模型和可拓集合理论的可拓评价方法, 其流程图如图 1 所示。

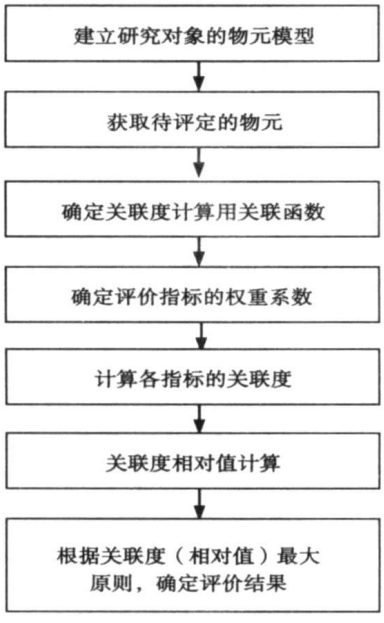

图 1 可拓评价方法流程简图

3.2 评价实例

3.2.1 建立待评物元

根据文献[1] 的实例: 某厂一台凝汽器在运行过程中, 凝汽器运行状态参数经过处理后, 其评价指标分别为: $X_{vac}=0.87$, $C_a=18$, $\delta_c=1$, $X_{ar}=200$, $X_{mtd}=0.9$, 构成凝汽器运行状态的待评物元(现状物元)为:

$$R_0=\begin{bmatrix} P_0, & X_{vac}, & 0.87 \\ & C_a, & 18 \\ & \delta_c, & 1 \\ & X_{ar}, & 200 \\ & X_{mtd}, & 0.9 \end{bmatrix} \tag{4}$$

3.2.2 计算关联函数值

根据前面 1.2.2 节的初等关联函数定义, 针对凝汽器运行状态评价的需要, 所采用的关联函数表示为:

$$K_{ij}(v_{ij})=\begin{cases} \dfrac{-\rho(v_{ij}, V_{ij})}{|V_{ij}|}, & \text{IF } v_{ij} \in v_{ij} \\ \dfrac{\rho(v_{ij}, V_{ij})}{\rho(v_{ij}, V_{pj})-\rho(v_{ij}, V_{ij})}, & \text{IF } v_{ij} \notin V_{ij} \end{cases} \tag{5}$$

式中: $K_{ij}(v_{ij})$—待评物元与凝汽器运行状态物元的关联函数; $\rho(v_{ij}, V_{ij})$—待评物元与各经典域的距; $\rho(v_{ij}, V_{pj})$—待评物元与节域的距; $|V_{ij}|$—经典域的量值大小, 其中 $|V_{ij}|=\left|\dfrac{b_{ij}-a_{ij}}{2}\right|$, $i=4$, $j=5$。

建立的可拓关联函数如图 2 所示。当 $0 \leqslant k(v) \leqslant 1$ 时, 表示 v 属于 V 的程度; 当 $k(v)<0$, 则称为 v 不属于 V 的程度。

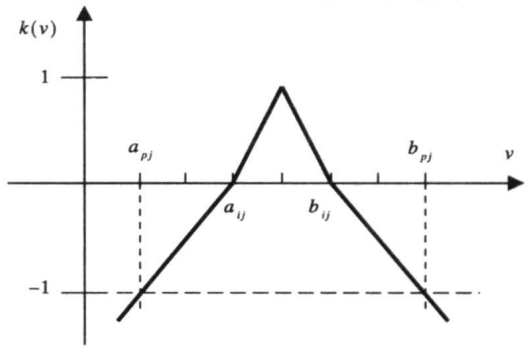

图 2 建立的关联函数示意图

3.2.3 确定权重系数

根据凝汽器运行状态中各评价指标凝汽器的安全和经济运行的作用大小(重要程度)及文献[1] , 这里取权重集合[W_{i1}, W_{i2}, …, W_{i5}] = [0. 50, 0. 10, 0. 15, 0. 15, 0. 10] 作为权重系数矩阵。

3.2.4 计算各状态指标的关联度

本例中各状态指标的关联度可参考文献[3] 按下式计算:

$$\lambda_i=\sum_j^5 W_{ij}K_{ij}, \quad i=1, 2, 3, 4 \tag{6}$$

计算结果分别为：[λ_1, λ_2, λ_3, λ_4] ＝[－0.170 8, －0.089 8, －0.294 6, －0.500 8] 。

3.2.5　计算各状态指标关联度的相对值

上面计算得到的状态指标的关联度值，不容易看出他们之间的相对大小，不利于状态等级的评价。为了使得各状态指标的关联度值均处于[－1, 1] 之间，以利于状态的评价，需要对各状态指标的关联度进行处理，得到各状态指标关联度的相对值。关联度的相对值可按下式进行计算：

$$\lambda'_i=\frac{2\lambda_i-\lambda_{\min}-\lambda_{\max}}{\lambda_{\max}-\lambda_{\min}},\ i=1,2,3,4 \qquad (7)$$

其中：$\lambda_{\max}=\max\limits_{1\leqslant i\leqslant 4}(\lambda_i)$；$\lambda_{\min}=\min\limits_{1\leqslant i\leqslant 4}(\lambda_i)$。

根据式(7)，本例的各状态指标关联度的相对值计算结果为：[λ'_1, λ'_2, λ'_3, λ'_4] ＝0.606 0, 1.000 0, 0.003 4, －1.000 0] 。

3.2.6　确定凝汽器运行状态优劣等级

凝汽器运行状态的优劣等级，可根据最大化原则利用下式判断：

$$\text{IF}(\lambda'_k=1)\text{THEN}(S_0=S_k) \qquad (8)$$

若 $\lambda'_k=1$，则判断运行状态等级为 S_k，其它状态等级的可能性可依据其关联度的相对值大小决定，一般关联度相对值越大，则意味着该状态等级出现的可能性越大。

因此根据这一原则，本例中的凝汽器各状态指标关联度的相对值分别为：0.606 0、1.000 0、0.003 4、－1.000 0，分别对应“优”、“良”、“合格”、“不合格”4 个等级。由式(8)可知，$\lambda'_2=1.000\ 0$，则凝汽器状态 $S_0=S_2$＝“良”，确定凝汽器运行状态等级为“良”，利用可拓评价方法得出的评判结果与文献[1] 的结果相同。

4　结　论

提出的基于物元模型和可拓关联函数为基础的凝汽器运行状态综合评价模型和方法，研究表明：

(1) 本方法可有效地处理凝汽器运行状态参数的多样性及模糊性特征，综合考虑各种主客观信息，能够定性和定量地评价凝汽器的状态；

(2) 所建立的物元模型简单，不需要大量的状态评价样本，计算时间短，评价结果更直观；

(3) 可利用计算机编制应用程序，能快速判别凝汽器的运行状态，是一种更为高效合理的凝汽器运行状态评价方法；

(4) 该方法可广泛应用于火电站动力设备及系统的状态评价、故障诊断及管理决策等方面，具有广阔的应用前景。

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（编辑　伟）

新设计

在具有喷嘴配汽的汽轮机调节级室内利用穿孔挡板

据《Тяжелое машиностроение》2007 年 1 月号报道，МЭИ（莫斯科动力学院）进行的研究结果表明，在给具有喷嘴配汽的汽轮机调节级部分进汽时，在调节级室内保持有速度和压力场很大的圆周不均匀性，这将对后面的高压部分各级产生不利的影响。

为了使进入汽轮机第一非调节级喷嘴装置的工质流动均匀，建议并研究了穿孔挡板，在最小成本的情况下利用这些挡板能使大功率汽轮机高压部分效率至少增加 1%。

容积式穿孔挡板结构的研究，可在任何发电用汽轮机上使用，其中包括 K－200－130 和 T－250－240 型汽轮机。

（吉桂明　供稿）

process, Numeca/design 3D software was used. By an optimized joint employment of an artificial neural network and a genetic algorithm, the general performance can be enhanced by way of an increase in localized performance. The flow field thus involved was calculated by seeking a solution for the full three-dimensional viscous flow N-S equation. Moreover, the authors have verified the feasibility of the method under discussion with a three-stage turbine and a four-stage one serving as examples. **Key words**: turbo-machinery, multi-stage turbine, aerodynamic optimization design, quasi three-dimensional design, design flow path, genetic algorithm, artificial neural network

涡轮静叶栅二次流的数值模拟=**A Study of the Numerical Simulation of Secondary Flows in Turbine Stator Cascades**[刊, 汉]/LI Jun, SU Ming (Education Ministry Key Laboratory on Turbo-machinery and Engineering, Shanghai Jiaotong University, Shanghai, China, Post Code: 200030)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —16~20

By adopting CFD (computational fluid dynamics) Software Fluent a numerical solution for the three-dimensional flows in turbine stator cascades featuring a big turning angle has been achieved. The secondary flows along the flow direction on various sections of the cascade and its aerodynamic characteristics were analyzed along with an investigation of the influence of any change in blade height and inlet incidence on cascade secondary flows. It has been found from the calculation results that the intensity of the secondary flows, which move from the cascade pressure surface to the suction one, increases gradually along the flow direction, giving rise to the continuous consolidation of the boundary layer on endwall near the suction surface and also a curling-up at the rear portion. Moreover, the foregoing also has led to a drastic change of the total pressure loss coefficient and the outlet flow angle along the blade height. A comparison of the various cascade operating conditions shows that a decrease of blade height and an increase of incidence will drastically increase the cascade secondary-flow losses, the intrinsic cause of which invariably lies in the expansion of the area occupied by the secondary flows in the cascade passage. **Key words**: secondary flow, turbine, stator cascade, numerical simulation

转子物性对超临界汽轮机启动热应力的影响=**The Influence of Rotor Physical Property on Thermal Stresses in a Supercritical Steam Turbine during its Startup**[刊, 汉]/LIU Yan-feng, HAO Run-tian, GAO Jian-qiang, et al (College of Energy Source and Power Engineering, North China Electric Power University, Baoding, China, Post Code: 071003)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —21~23

In most cases steam turbine rotors are made of 30CrMoV low carbon alloy steel, the physical property parameters of which change significantly with temperature. The model established for calculating rotor thermal stresses has taken into account the influence of the temperature-dependent change of rotor-material physical property. Through a simulation test, analyzed was the variation tendency of rotor thermal stresses in a domestically-made 600 MW supercritical steam turbine under the following four start-up operating conditions, namely, cold-state, warm-state, hot-state and extremely-hot-state. Moreover, the tendency in question was compared with that obtained from a thermal-stress model featuring a rotor of constant physical property. It has been shown that the change of rotor material physical parameters with temperature will significantly influence the magnitude of the start-up thermal stresses. The above finding can provide a helpful reference for enhancing the calculation accuracy of an on-line monitoring model involving turbine-rotor thermal stresses. **Key words**: steam turbine rotor, physical property, thermal stress, model

凝汽器运行状态的物元模型及可拓评价方法=**An Object-element Model for Depicting the Operating States of a Condenser and its Extensible Evaluation Method**[刊, 汉]/LU Xu-xiang, LI Lu-ping (College of Energy Source and Power Engineering, Changsha University of Science and Technology, Changsha, China, Post Code: 410076)//Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —24~27

On the basis of establishing indexes for evaluation of the operating states of condensers, presented was an extensible method for the above evaluation in the light of diversity and fuzziness of the evaluation indexes. The proposed method was based on an object-element model and extensible correlation functions. In combination with currently available literature

and extension theories, the object-element model for appraising the operating status of a condenser was established and a group of extensible correlation functions was used to calculate the correlation between the condenser operating-state parameters and various status grades. Then, based on the magnitude of the correlation in question, a qualitative and quantitative evaluation of the condenser operating state was conducted. Finally, the practicability of the method under discussion was verified by a specific case calculation. The research findings show that the method in question can quickly and effectively identify the operating state of a condenser, thus providing a new approach for the latter' s evaluation. **Key words**: condenser, status evaluation, extension theory, object-element model, correlation function

燃气轮机带冠涡轮动叶故障分析及改进= **Fault Analysis of Shrouded Moving Blades of a Gas Turbine and Trouble-saving Measures**[刊, 汉] / LI Gui-ying, WEN Xue-you, LI Dong-ming, et al (No. 703 Research Institute of China Shipbuilding Industry Corporation, Harbin, China, Post Code: 150036) // Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —28 ~ 31

By adopting statics and dynamics calculation methods, a corner falling-off occurring on shrouded moving blades of an industrial gas turbine was analyzed and the major cause of the fault, identified. The latter lies in an excessive pre-twisted angle of the originally designed blade shrouds, a relatively small fillet radius R at the blade shroud concave and improper assembly procedures. Blade structure design and assembly procedures have been improved based on the analytic calculation results. The blade pre-twisted angle of 1° has been adjusted to 0.5° and the fillet radius R of the blade shroud concave, increased from 0.8 mm to 2 mm. Moreover, the transition radius R from the leading edge on the blade pressure surface to the shroud has been increased from 3 mm to 4.5 mm. The subsequent operation has proved the effectiveness of the implemented measures. **Key words**: turbine shrouded moving blades, blade shroud, blade assembly

热电发电机驱动热电热泵联合循环热力学分析= **Thermodynamic Analysis and Optimization of the Combined Cycle of a Thermoelectric Heat Pump Driven by a Thermoelectric Generator**[刊, 汉] / MENG Fan-kai, CHEN Lin-gen, SUN Feng-rui (Postgraduate College, Naval University of Engineering, Wuhan, China, Post Code: 430033) // Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —32 ~ 36

An innovative model for the combined cycle of a thermoelectric pump driven by a thermoelectric generator was established, and on the basis of non-equilibrium thermodynamic theory, the performance of the whole plant, also analyzed. An analytic formula involving such parameters as the heat supply rate, non-dimensional heat supply rate, as well as the ratio of heat supply coefficient and thermoelectric elements etc. has been derived. Studied was the optimal working current and thermoelectric element distribution corresponding to the maximal heat supply rate and coefficient of the plant. Analyzed was the influence of the high temperature heat-source temperature of the generator and heat-pump heat-supply space temperature etc. on the heat supply rate, heat supply coefficient and the optimal working current and thermoelectric element distribution of the plant. Furthermore, the curve showing the relationship of the heat supply coefficient and non-dimensional heat supply rate at different temperatures of the generator heat source was also given. **Key words**: combined thermoelectric plant, thermoelectric generator, thermoelectric heat pump, non-equilibrium thermodynamics

一种新型的无级调速装置的开发和研究= **Development and Study of a New Type of Stepless Speed Control Device**[刊, 汉] / YUAN Bin, CHEN Ning, XU Jun-min (College of Mechanical and Automobile Engineering, Zhejiang University of Science and Technology, Hangzhou, China, Post Code: 310023), QIU Min-xiu (National Key Laboratory on Fluid Power Transmission and Control, Zhejiang University, Hangzhou, China, Post Code: 310027) // Journal of Engineering for Thermal Energy & Power. —2008, 23(1). —37 ~ 40

The basic working principle of a hydro-viscous drive (HVD) was described, and the overall structure of the HVD along with its hydraulic system, designed. A prototype sample machine was manufactured, which underwent an experimental study. On the basis of the test results, an exploratory study was performed of several key technical issues demanding special attention during the design of the HVD. The study shows that the 400 kW HVD developed on the basis of the design