

# 燃气机热泵部分负荷特性的实验研究

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**摘 要:** 对燃气机热泵机组进行了部分负荷特性实验研究, 重点分析了末端水流量和转速对其制热性能的影响规律。结果表明: 冷凝器负荷、总余热、性能系数和一次能源利用率均随末端水流量的增大而增大, 当末端水流量由  $1.8 \text{ m}^3/\text{h}$  增大到  $3.6 \text{ m}^3/\text{h}$  时, 性能系数和一次能源利用率分别增大 11.6% 和 19.5%; 冷凝器负荷和总余热随发动机转速的升高而增大, 但是性能系数和一次能源利用率随转速由 1 300 升高到 2 000 r/min 时, 分别减小 40% 和 9.8%。燃气机热泵机组在不同末端水流量和燃气发动机转速工况下均具有良好的部分负荷特性。

**关 键 词:** 燃气机热泵; 制热工况; 变末端水流量; 变转速; 部分负荷

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## 引 言

以天然气作为能源的燃气机热泵<sup>[1~5]</sup> (GEHP, Gas Engine-driven Heat Pump) 在美国、日本和欧洲国家得到了广泛的应用, 而在我国, GEHP 尚属起步阶段。与普通的电驱动热泵 (EEHP, Electric Engine-driven Heat Pump) 相比, 由于燃气机热泵能够充分利用发动机的余热, 所以其比电驱动热泵具有更好的供热性能。为了探索燃气机热泵系统运行规律及其进一步示范性应用, 本研究针对燃气机热泵机组进行了变末端水流量和转速的实验研究, 分析了末端水流量、转速与冷凝器负荷、总余热、性能系数以及一次能源利用率的关系, 得到燃气机热泵机组在部分负荷下的性能系数和一次能源利用率等参数变化规律。

## 1 燃气机热泵实验台

燃气机热泵实验台如图 1 所示, 系统包括制冷剂循环、余热循环和末端循环三部分。该系统在制冷和制热时能够充分回收发动机缸套废热和排烟废

热, 这两部分余热主要用于以下两个方面: (1) 在制热模式下, 燃气发动机余热大部分用于供热; (2) 制冷模式下, 燃气发动机余热提供生活热水。由于能够充分回收燃气发动机余热, 燃气机热泵系统具有较高的一次能源利用率和较好的节能环保效果。

图 1 所示, 末端水流量由智能涡旋流量计  $F_3$  实时记录, 房间回水经冷凝器后, 进板式换热器 (水-水), 进一步与缸套余热和排烟余热进行换热, 提高其出水温度。燃气机热泵开机阶段, 当膨胀水箱温度低于  $55^\circ\text{C}$ , 截止阀  $V_2$  开启, 直到温度达到设定值, 以此保证燃气发动机具有较高的效率。

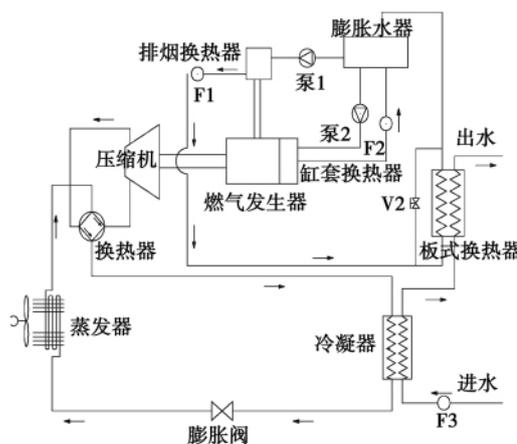


图 1 燃气机热泵系统

Fig. 1 A gas turbine heat pump system

## 2 系统数据分析

燃气发动机的转速和扭矩保持不变时, 发动机处于稳态工况。燃气发动机的一次能耗由天然气的流量以及其低位热值通过式 (1) 计算, 可得:

$$Q_f = G_f \cdot e_f \quad (1)$$

式中:  $Q_f$ —发动机的一次能耗, kW;  $G_f$ —天然气流

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量  $\text{kg/s}$ ;  $e_f$ —天然气低位热值  $\text{kJ/kg}$ 。

燃气机热泵系统冷凝器负荷,在忽略冷凝器热损失情况下,冷凝器热负荷由式(2)计算:

$$Q_e = G_{\text{ref}}(h_2 - h_3) = G_{w3}c_{pw}(t_{\text{out}} - t_{\text{in}}) \quad (2)$$

式中:  $Q_e$ —冷凝器负荷  $\text{kW}$ ;  $G_{\text{ref}}$ —制冷剂流量  $\text{kg/s}$ ;  $h_3$ —冷凝器出口比焓  $\text{kJ/kg}$ ;  $h_2$ —冷凝器进口比焓  $\text{kJ/kg}$ ;  $G_{w3}$ —冷凝器进水流量  $\text{kg/s}$ ;  $c_{pw}$ —水的比热  $\text{kJ}/(\text{kg} \cdot ^\circ\text{C})$ ;  $t_{\text{out}}, t_{\text{in}}$ —冷凝器出、进水温度  $^\circ\text{C}$ 。

系统余热包括缸套余热和烟气余热,发动机稳定在某一工况时,基于能量守恒原理,通过测量发动机冷却水流量、进出口温度、烟换热器水流量和进出口温度,根据采集的相关数据,可得到缸套余热公式(3)和烟气余热公式(4),则:

$$Q_{\text{cj}} = G_{w1}c_{pw}(t_{w2} - t_{w1}) \quad (3)$$

$$Q_{\text{exh}} = G_{w2}c_{pw}(t_{w4} - t_{w3}) \quad (4)$$

式中:  $Q_{\text{cj}}$ —缸套余热  $\text{kW}$ ;  $G_{w1}$ —发动机冷却水流量  $\text{kg/s}$ ;  $t_{w1}, t_{w2}$ —冷却水进、出口温度  $^\circ\text{C}$ ;  $Q_{\text{exh}}$ —烟余热  $\text{kW}$ ;  $G_{w2}$ —制取的热水量  $\text{kg/s}$ ;  $t_{w3}, t_{w4}$ —制取的热水电进出口温度  $^\circ\text{C}$ 。

缸套换热器以及烟换热器水流量  $G_{w1}$  和  $G_{w2}$  只与燃气发动机转速有关,分别由智能涡旋流量计测量,如图1中  $F_1$  和  $F_2$ 。通过实验,对数据进行拟合分析,得到流量与转速的关系如图2所示。

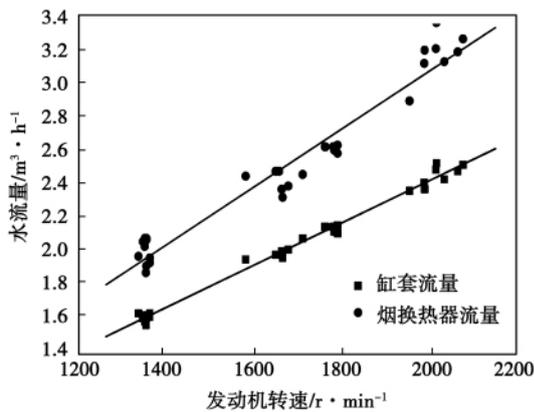


图2 冷却水流量和转速的关系

Fig. 2 Relationship between the circulating water flow rate and the rotating speed

与常规电动热泵相比,由于回收发动机余热,对整个燃气机热泵系统,定义系统的性能系数  $COP_t$ ,如式(5)所示,一次能源利用率  $PER_t$  通过式(6)求解得:

$$COP_t = (Q_e + Q_{\text{cj}} + Q_{\text{exh}}) / Q_{\text{com}} \quad (5)$$

$$PER_t = (Q_e + Q_{\text{cj}} + Q_{\text{exh}} + Q_{\text{gen}}) / Q_f \quad (6)$$

式中:  $Q_{\text{com}}$ —压缩机的轴功  $\text{kW}$ ;  $Q_{\text{gen}}$ —发电机输出功率  $\text{kW}$ 。通过上位机采集的数据,联立上式可对燃气机热泵性能参数进行计算分析。

### 3 系统制热性能分析

#### 3.1 末端水流量对系统参数的影响

##### 3.1.1 冷凝器负荷随末端水流量的变化规律

图3为系统冷凝器负荷随末端水流量的变化规律。在发动机保持某一转速不变的情况下,末端水流量影响板式换热器水侧的换热系数以及制冷剂和水的总换热系数,从而使板式换热器内的传热温差和换热效率发生变化,进而影响整个系统的性能。末端水流量的增大,使制冷剂和水的总换热系数增大,从而使冷凝器负荷升高,即冷凝器负荷随着末端水流量的增大而增大。

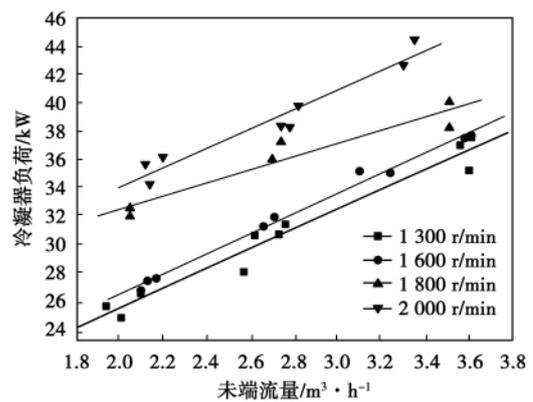


图3 冷凝器负荷随末端水流量的变化

Fig. 3 Change of the load of a condenser with the water flow rate at an end

##### 3.1.2 总余热随末端水流量的变化规律

图4是系统的总余热与末端水流量的关系。在发动机转速为  $1300 \text{ r/min}$  时,随着末端水流量的增大,总余热变化较小,这表明发动机在转速为  $1300 \text{ r/min}$  时输出的轴功随着负荷的增加而变化较小,即  $1300 \text{ r/min}$  时发动机的轴功完全大于因末端水流量增大而引起的压缩机轴功的增幅。在转速高于  $1600 \text{ r/min}$  时,总余热与末端水流量成线性升高趋势,这是因为冷凝器负荷的增加,使压缩机轴功率增大,从而使燃气发动机的一次能耗增加,而总余热随系统能耗的增大而增大。因此,总余热随末端水流量呈线性增大变化。

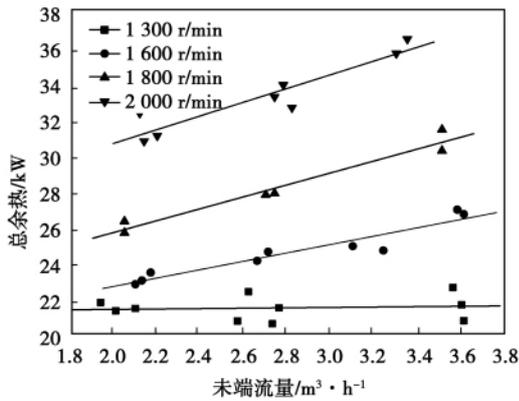


图 4 系统总余热随末端水流量的变化

Fig. 4 Change of the total waste heat in a system with the water flow rate at an end

### 3.1.3 性能系数随末端水流量的变化规律

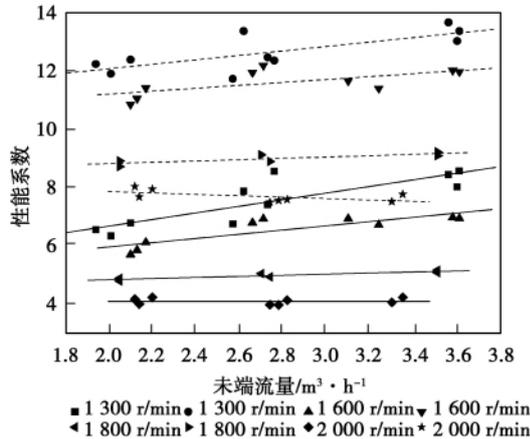


图 5 系统性能系数随末端水流量的变化

Fig. 5 Change of the systematic performance with the water flow rate at an end

图 5 是系统的性能系数随末端水流量的变化规律,虚线为回收发动机余热后系统性能系数  $COP_t$ ,实线所示为系统无回收发动机余热时性能系数  $COP$ 。由图可知,系统的性能系数随末端水流量的增大而升高。系统的性能系数在发动机转速为 1 300 r/min 时变化较大。末端水流量由 1.8  $m^3/h$  增加到 3.6  $m^3/h$  时,冷凝器负荷和系统的总余热分别增大 45% 和 4.1%。而此时,因冷凝器负荷增大而导致压缩机功率增大 12.9%。综合这 3 方面的效果,回收余热后的系统的性能系数  $COP_t$  相应增大 11.6%;当燃气发动机转速升高时,系统的性能系数和一次能源利用率斜率有所减小,即系统性能系数的增幅减小。这是因为燃气发动机转速升高时,系统

制冷剂流量增大,冷凝器内制冷剂侧换热系数因流量的增大而增大,制冷剂和水传热温差减小,换热效果增强,冷凝器负荷增大。即使末端流量增大,冷凝器内水和制冷剂的换热系数则变化较小,加之,燃气发动机转速的升高,导致压缩机轴功增大,所以在燃气发动机高转速情况下,系统的性能系数增加幅度较小。

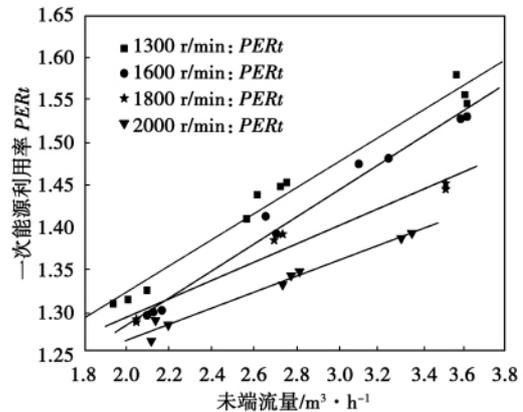


图 6 系统一次能源利用率随末端水流量的变化

Fig. 6 Change of the primary energy utilization rate of a system with the water flow rate at an end

图 6 所示系统的一次能源利用率  $PER_t$  随末端水流量的变化,随着末端水流量的增大,  $PER_t$  增大,最高达到 1.61。在转速为 1 300 r/min 时,系统的总供热量增大 26%,而此时,发动机的一次能耗却增加 4.4%。由于系统总供热量增加的幅度大于发动机一次能耗的增加,所以系统的一次能源利用率  $PER_t$  增大 19.5%。

### 3.2 转速对系统参数的影响

#### 3.2.1 冷凝器负荷随转速的变化规律

图 7 是系统的冷凝器负荷随发动机转速的变化规律。由图可知,在某一末端水流量下,冷凝器负荷随着发动机转速的升高而增大。压缩机的转速和发动机的转速是一一对应的关系,当发动机的转速升高时,压缩机的转速同样升高。压缩机转速的升高导致系统的制冷剂流量增大,从而使冷凝器负荷增大。

#### 3.2.2 总余热随转速的变化规律

图 8 是系统的总余热随发动机转速的变化规律,即随发动机转速的升高而明显增大。由图 7 可知,发动机转速的升高导致冷凝器负荷增大,系统的制冷剂流量增大,从而使压缩机的耗功增加,发动机的功率随压缩机耗功的增加而变大,那么发动机的

一次能耗随之增加,通过发动机缸套和排烟获得的总余热增大。

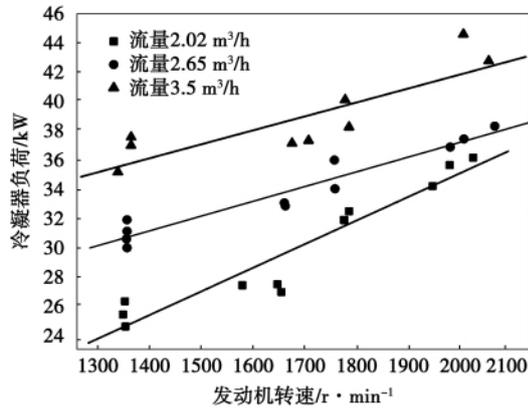


图7 冷凝器负荷随转速的变化

Fig. 7 Change of the load of a condenser with the rotating speed

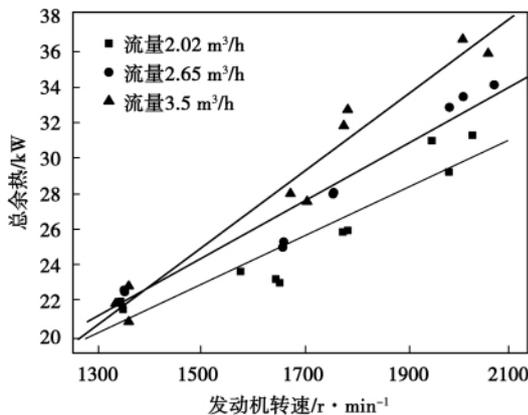


图8 系统总余热随转速的变化

Fig. 8 Change of the total waste heat of a system with the rotating speed

### 3.2.3 性能系数随转速的变化规律

图9是系统的性能系数随发动机转速的变化规律,虚线为回收发动机余热后系统性能系数 $COP_i$ ,实线所示为系统无回收发动机余热时性能系数 $COP$ 。在不同末端水流量时,系统的性能系数均随发动机转速的升高而减小。在末端水流量为 $3.5\text{ m}^3/\text{h}$ 时,发动机转速由 $1300\text{ r}/\text{min}$ 升高到 $2000\text{ r}/\text{min}$ 时,系统的制冷剂流量增大而使冷凝器负荷增大 $22\%$ ,发动机总余热增加 $65\%$ 。但是,压缩机的功率随之增大 $1.38$ 倍。由于压缩机功率增大的幅值大于系统总供热量增大的幅值,所以系统的性能系数 $COP_i$ 减小 $40\%$ ,这与文献[6]的系统性能系数

随燃气发动机转速的升高而降低的结论相一致。

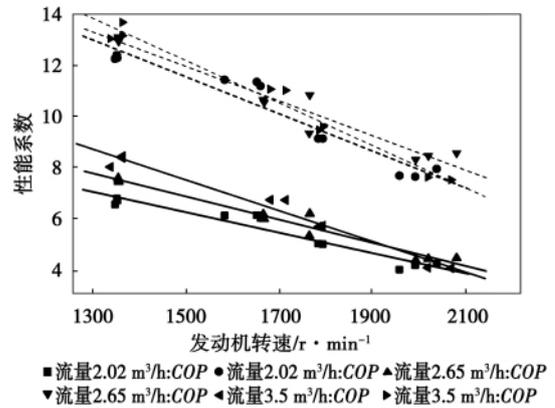


图9 系统性能系数随转速的变化

Fig. 9 Change of the performance coefficient of a system with the rotating speed

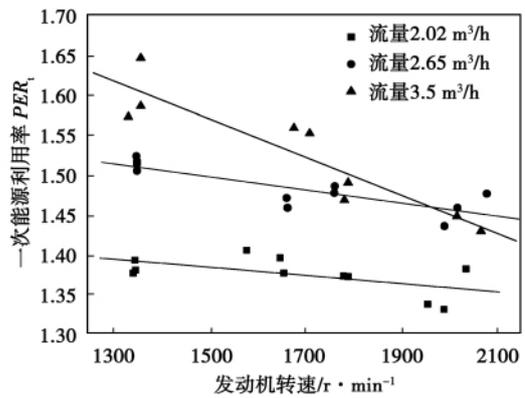


图10 系统一次能源利用率随转速的变化

Fig. 10 Change of the primary energy utilization rate of a system with the rotating speed

图10所示系统的一次能源利用率 $PER_t$ 随发动机转速的变化曲线,随着发动机转速的升高, $PER_t$ 成减小趋势。在末端水流量为 $3.5\text{ m}^3/\text{h}$ 时,发动机转速由 $1300\text{ r}/\text{min}$ 升高到 $2000\text{ r}/\text{min}$ 时,冷凝器负荷和系统的总余热均增大,系统的总供热量增大 $40.2\%$ 。但是转速升高导致系统的制冷剂流量增大和压缩机耗功增加,从而使发动机的一次能耗增大 $50\%$ ,一次能耗的增幅大于系统总供热量的增幅,所以系统的一次能源利用率 $PER_t$ 减小 $9.8\%$ 。此时,系统的一次能源利用率 $PER_t$ 仍然保持在 $1.45$ 以上。

## 4 结 论

对燃气机热泵系统在制热工况下进行了实验研究,着重分析了末端水流量以及燃气发动机转速对系统冷凝器负荷、总余热、系统性能系数以及一次能源利用率的影响。结论如下:

(1) 冷凝器负荷、总余热以及系统的性能系数均随末端水流量的增大而增大。在发动机转速为 1 300 r/min 时,末端水流量由 1.8 增大到 3.6 m<sup>3</sup>/h,系统的性能系数  $COP_1$  增加 11.6%,一次能源利用率  $PER_1$  增加 19.5%。

(2) 冷凝器负荷和总余热随发动机转速的升高而增大,但是性能系数却随转速的升高而减小。在末端水流量为 3.5 m<sup>3</sup>/h 时,发动机转速由 1 300 r/min 升高到 2 000 r/min 时,系统的性能系数  $COP_1$  明显减小 40%。系统的一次能源利用率  $PER_1$  减小 9.8%。

(3) 燃气机热泵系统具有良好的部分负荷性能,通过对转速的调整能够较好的匹配负荷的变化、满足供暖需求。

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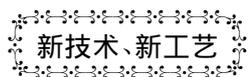
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新技术、新工艺

## 涡轮级内扰动力的试验测定

据《Тяжёлое машиностроение》2010年12月报道,由于缺少气动扰动力和减振方面的数据资料,目前尚不能计算和评定涡轮机叶片内的共振应力。叶片装置处于旋转状态下的振动试验可以得到相关减振的试验数据,此时根据共振曲线的宽度来确定振动的衰减量。

在实物汽轮机末级动叶片上完成了涡轮负荷和压比  $P_2/P_0$  对共振叶片动应力级影响的试验研究。

得到了8倍率扰动力相对变幅随级工作气动力参数而变化的关系,该关系式可用于几何类似级的估算。

(吉桂明 摘译)

Chinese Academy of Sciences , Beijing , China , Post Code: 100190) //Journal of Engineering for Thermal Energy & Power. - 2010 26( 5) . - 513 ~ 517

By using a numerical simulation method , studied was the influence of the hole-row spacing on the air-film cooling characteristics of a dual jet flow with a composite angle at different air ratios. It has been found that the reverse kidney shaped vortex formed by a relatively small hole-row spacing is of a upper and lower structure and unsymmetrical and the improvement of the air-film cooling effectiveness is limited while a relatively large hole-row spacing is favorable for forming a right and left symmetrical reverse kidney shaped vortex , capable of forming a large area cooling air coverage along the chord direction at the lower reaches and meanwhile making the jet flow attached to the wall surfaces better , thus greatly enhancing the cooling efficiency. Such a structure was applied in the stator blades of a heavy-load gas turbine and a good cooling effectiveness was achieved. **Key words:** air-film cooling , dual jet flow , hole-row spacing , reverse-kidney-shaped vortex

微型燃气轮机 CW 原表面回热器芯体内传热及阻力特性分析 = **Analysis of the Heat Transfer and Flow Resistance Characteristics Inside the Core Body of a Cross Wavy Primary Surface Recuperator in a Micro Gas Turbine** [刊 汉] / GUI Xiao-hong , LIANG Shi-qiang ( Engineering Thermophysics Research Institute , Chinese Academy of Sciences , Beijing , China , Post Code: 100190) , YAN Run-sheng , CHENG Yan-jun ( Light Industry Environmental Protection Research Institute , Beijing , China , Post Code: 100089) //Journal of Engineering for Thermal Energy & Power. - 2011 , 26( 5) . - 518 ~ 522

With a 3-D periodically fully developed numerical calculation model for a cross wavy ( CW) primary surface recuperator in a micro gas turbine being established , analyzed were the heat transfer and flow resistance characteristics inside the core body. Moreover , the influence of the mass flow rate and temperature on the heat quantity exchanged and the pressure drop was determined and the empirical correlation formula among the in-plate flow resistance , heat transfer factors , Nusselt number and Reynolds number of the CW primary surface recuperator was given. The heat transfer and flow resistance performance analytic results show that with an increase of the Reynolds number , the heat transfer coefficient of the recuperator core unit will increase and the heat transfer quantity will gradually increase. With a rise of the temperature at the inlet of the LP high temperature flue gas side , the extent of the increase in heat transfer quantity will grow. The recuperative degree of the recuperator core unit will decrease with an increase of the Reynolds number and the temperature of the gas at the inlet. **Key words:** Micro gas turbine , CW ( cross wavy) primary surface recuperator , heat transfer , flow resistance , periodically full development

燃气机热泵部分负荷特性的实验研究 = **Experimental Study of the Partial Load Characteristics of a Gas-engine-driven Heat Pump** [刊 汉] / LIU Huan-wei , YANG Zhao , WANG Ming-tao ( Thermal Energy Research Institute , Tianjin University , Tianjin , China , Post Code: 300072) //Journal of Engineering for Thermal Energy & Power. - 2011 , 26( 5) . - 523 ~ 527

Experimentally studied were the partial load characteristics of a gas-engine-driven heat pump unit and mainly analyzed was the law governing the influence of the end water flow rate and rotating speed on the heat production performance of the unit. It has been found that the load of the condenser, total waste heat, performance coefficient and primary energy source utilization rate will all increase with an increase of the end water flow rate. When the end water flow rate increases from  $1.8 \text{ m}^3/\text{h}$  to  $3.6 \text{ m}^3/\text{h}$ , the performance coefficient and primary energy source utilization rate will increase by 11.6% and 19.5% respectively. The load of the condenser and the total waste heat will increase with an increase of the rotating speed of the engine and the performance coefficient and the primary energy source utilization rate, however, will decrease by 40% and 9.8% respectively when the rotating speed of the engine increases from 1300 r/min to 2000 r/min. The gas-engine-driven heat pump unit boasts good partial load characteristics at various end water flow rates and rotating speeds of the gas-engine. **Key words:** gas-engine-driven heat pump, heat production operating condition, variable end water flow rate, variable speed, partial load

纳秒脉冲等离子体气动激励控制平板附面层的研究 = **Study of the Boundary Layer on a Plate Aerodynamically Excited and Controlled by Using Nanosecond Pulse Plasma** [刊, 汉] YUE Tai-peng, LI Ying-hong, SUN Dong, CUI Wei (Engineering College, Air Force Engineering University, Xi'an, China, Post Code: 710038) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(5). - 528 ~ 532

To study the working mechanism of the boundary layer on a plate aerodynamically excited and controlled by using nanosecond pulse plasma and the law governing its change under different parameters, the speed of air flow aerodynamically excited and controlled by using the nanosecond pulse plasma was measured by utilizing a self-developed velocity measurement system. The measurement results show that under different combined excitation modes, the aerodynamic excitation effectiveness by using the plasma is varied and that produced by using the medium barrier discharge is regarded as the best. That achieved by using the nanosecond plasma to excite and induce the air to accelerate will be enhanced with an increase of the excitation voltage. Its effectiveness played on a low speed air flow is better than that on a high speed air flow. The jet flow direction aerodynamically excited and induced by using the nanosecond pulse plasma forms a certain angle with the wall surface. Along the downstream direction, the air flow acceleration effectiveness aerodynamically excited and induced by using the plasma is weakened obviously. **Key words:** aerodynamic excitation by using plasma, boundary layer, induction, excitation combination, medium barrier discharge

辐射传热定律下外燃机最大输出功率优化 = **Optimization of the Maximum Power Output of an External Combustion Engine Under the Law of Radiation-based Heat Conduction** [刊, 汉] MA Kang, CHEN Lin-gen, SUN Feng-ru (Postgraduate School, Naval Engineering University, Wuhan, China, Post Code: 430033) // Journal of Engineering for Thermal Energy & Power. - 2011, 26(5). - 533 ~ 537

With a piston-type external combustion engine serving as an object of study, optimized was an external combustion