

超临界工况下回热器对低温余热发电系统性能的影响

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摘 要: 为研究超临界工况下增加回热器对低温余热发电系统性能的影响,建立了带回热器的超临界有机朗肯循环计算模型;指出了在超临界工况下由一般方法计算有机朗肯循环的热力参数存在一定偏差,运用 EES(Engineering Equation Solver) 软件对有、无回热器两种情况下系统的热力参数进行了计算。研究表明:在超临界工况下,以 R152a 为工质,系统增加回热器后最大热效率提高了 0.65%,对应的蒸发压力降低了 494 kPa;系统焓效率有所提高,但增加幅度有限;多目标优化发现,增加回热器后系统最佳工况点为蒸发压力 4 654 kPa,比无回热器时降低了 318 kPa。

关 键 词: 低温余热发电;超临界;有机朗肯循环;回热器;多目标优化

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引 言

温度在 350℃ 以下的低温余热普遍存在于工业过程中,其来源广泛、数量巨大;回收和利用这部分余热,既有助于缓解我国能源紧张的局势,又能减少工业生产过程中的环境污染,其节能减排的效果具有十分重要的现实意义^[1~2]。基于有机朗肯循环(Organic Rankine Cycle,简称 ORC)的余热发电系统能够将低品位余热转换为高品位电能,是提高能源利用效率和降低环境污染的有效途径^[3~4];因其显著的优点以及广阔的应用前景,各国学者对其进行了广泛的研究。魏东红等人以 R245fa 为工质^[5~6],分析了烟气流量和温度、过冷度以及环境温度等对系统性能的影响;Maizza 等人比较了不同种类有机工质的效率^[7];Saleh 等人分析了有、无回热器时不同工质效率变化的关系^[8];徐杰等人以系统热效率最大为计算原则^[9],提出以 R123 为工质的有机朗肯循环系统中最佳再热压力的确定方法;刘广彬等人研究了余热发电系统中膨胀机的输出特性^[10];还有针对 ORC 系统在回收地热能、太阳能和海水淡化等方面应用的研究^[11]。研究热点主要集中在循环

工质的选择、系统热力学分析、膨胀机的设计,以及系统性能评价等方面。

目前,对余热发电系统的研究大多是基于亚临界工况下的有机朗肯循环;而在超临界 ORC 系统中,膨胀机出口工质的温度较亚临界工况时的温度要高出许多,增加回热器能够有效地降低冷凝器入口工质温度,同时提高蒸发器入口工质的温度。从目前文献来看,对于超临界工况下 ORC 余热发电系统的研究相对较少。本研究采用 EES 软件对超临界工况下循环系统的热力参数进行计算,并采用多目标优化模型对系统性能进行分析,其研究方法和分析结果可为工程实际中超临界有机朗肯循环系统的设计研究提供参考。

1 超临界 ORC 系统及工质参数

1.1 超临界 ORC 系统

带回热器的超临界 ORC 系统是在常规 ORC 系统的基础上增加了回热器,并工作在超临界工况下。由于工质在超临界压力下的吸热过程不存在亚临界压力下的定温蒸发阶段,这种不断吸热的变温过程能很好地与余热介质变温特性匹配,因此采用超临界 ORC 在理论上能较好地逼近变温热源驱动下的理想循环,从而获得较高的系统热效率。其系统流程如图 1 所示;有机工质依次在蒸发器中吸热、膨胀机中做功、回热器中换热和冷凝器中放热,再经过加压泵升压再次进入蒸发器,完成一个循环,从而实现了余热资源从低品位热能到高品位电能的转换。

1.2 工质参数

工质对 ORC 系统的安全性、环保性、经济性,以及高效性具有很大的影响,合适的工质应满足低毒、不燃、无腐蚀,具有较好的材料兼容性和热稳定性,同时使系统具有较高的热效率和适中的蒸发压力^[12]。R152a 是一种性能优越的制冷剂,具有较低

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的临界温度(113. 26 °C) 和临界压力(4. 52 MPa) , 能较容易实现超临界动力循环; 选用 R152a 为循环工质, 其相关物性参数如表 1 所示。

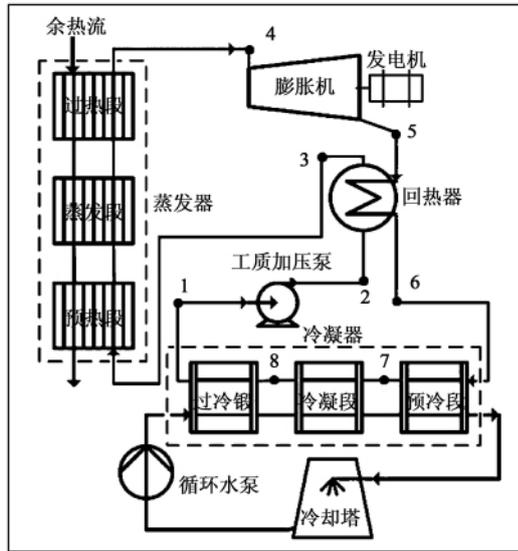


图 1 带回热器的超临界 ORC 系统流程图

Fig.1 Flow chart of a supercritical ORC system with a recuperator

表 1 R152a 物性参数

Tab.1 Physical parameters of R152a

参数名称	参数值
摩尔质量/kg · kmol ⁻¹	66.05
沸点/°C	-24.023
临界压力/MPa	4.52
临界温度/°C	113.26
临界密度/kg · m ⁻³	368
破坏臭氧层潜能值 ODP	0
全球变暖系数值 GWP	2.8

2 ORC 系统模型建立及计算

2.1 ORC 系统热力循环及其 EES 编程的实现

为了简化系统模型, 建模过程中做了如下假设:

①整个系统状态稳定; ②忽略管道散热损失; ③整个系统循环中忽略化学反应能。系统循环 $T-s$ 图如图 2 所示。

(1) 状态点 1—2, 为工质加压过程, 泵所耗功为:

$$W_{\text{pump}} = P_{\text{ideal}} / (\eta_p \cdot \eta_m) = q_m (h_{2s} - h_1) / (\eta_p \cdot \eta_m) \quad (1)$$

式中: P_{ideal} —工质泵的理想功率, kW; η_p 、 η_m —泵的绝热效率和机械效率; h_1 、 h_{2s} —工质泵等熵加压过程中进出口比焓, kJ/kg; q_m —有机工质质量流量, kg/s;

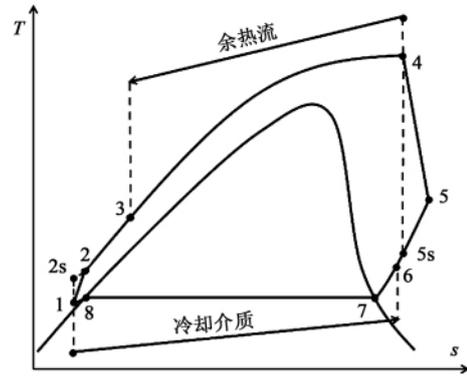


图 2 带回热器的超临界朗肯循环 $T-s$ 图

Fig.2 $T-s$ diagram of a supercritical ORC system with a recuperator

(2) 状态点 2—3、5—6, 为回热器中冷热工质换热过程, 热平衡关系式:

$$h_3 - h_2 = h_5 - h_6 \quad (2)$$

(3) 状态点 3—4, 为工质在蒸发器中的吸热过程, 吸热量为 Q_{eva} , kW:

$$Q_{\text{eva}} = q_m (h_4 - h_3) \quad (3)$$

(4) 状态点 4—5, 为工质在膨胀机中的绝热膨胀过程, 膨胀机做功为:

$$W_T = W_{T \text{ ideal}} \cdot \eta_{Tj} \cdot \eta_{Tm} = q_m (h_4 - h_{5s}) \cdot \eta_{Tj} \cdot \eta_{Tm} \quad (4)$$

式中: h_4 、 h_{5s} —膨胀机等熵膨胀时进出口比焓, kJ/kg; η_{Tj} 、 η_{Tm} —膨胀机内效率和机械效率;

(5) 状态点 6—7—8—1, 可视为等压冷凝过程, 换热量 Q_{cond} , kW 为:

$$Q_{\text{cond}} = q_m (h_6 - h_1) \quad (5)$$

采用 EES 软件对超临界 ORC 系统模型进行编程求解^[13-14], 热力循环部分状态点参数计算的主要程序为:

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h8 = enthalpy( R152a t = Tcon x = 0 );
P8 = pressure( R152a t = Tcon x = 0 );
T8 = Tcon; Pcon = P8; P1 = Pcon;
T1 = T8 - tsub; { tsub 为过冷度}
h1 = enthalpy( R152a t = T1 p = P1 );
s1 = entropy( R152a t = T1 p = P1 );
h2s = enthalpy( R152a p = Peva s = s1 );
    
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$h_2 = (h_{2s} - h_1) / n_{p} + h_1$; { n_p 为工质泵的绝热效率}

$q_{eva} = h_4 - h_3$; $T_4 = T_{gas_in} - \Delta T$;

{ T_{gas_in} 为蒸发器中烟气入口温度, ΔT 为烟气入口温度端差}

$h_4 = \text{enthalpy}(R152a, t = T_4, p = P_{eva})$;

$s_4 = \text{entropy}(R152a, t = T_4, p = P_{eva})$;

$h_{5s} = \text{enthalpy}(R152a, p = P_{con}, s = s_4)$;

$h_5 = h_4 - (h_4 - h_{5s}) * n_T$;

{ n_T 为泵绝热效率}

$w_T = (h_4 - h_5) * n_{Tm}$;

$w_{pump} = (h_2 - h_1) * n_m$;

$w_{net} = w_T - w_{pump}$;

.....

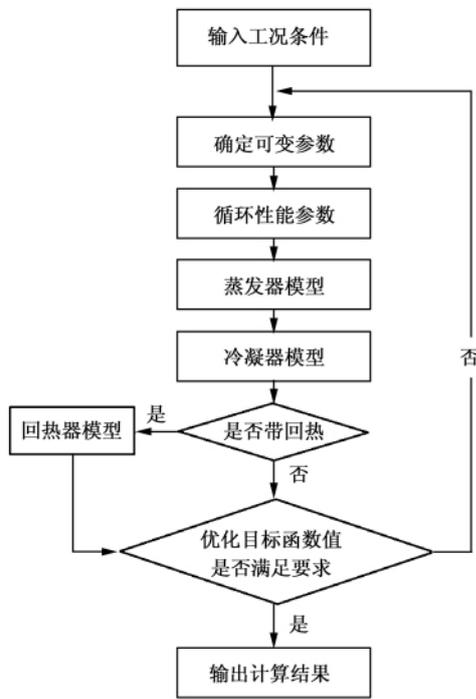


图 3 低温余热发电 ORC 系统全局模型求解程序流程图

Fig. 3 Flow chart of the solution-seeking program for a low temperature waste heat power generation ORC system by using the overall model

算法如图 3 所示。首先,确定不变(或变化很小)的参数值以及可变参数的取值范围;一旦可变参数的值选定,循环中每个点的状态参数就可以通过该程序求出,进而可以分析求得系统的循环性能指标;然后,通过蒸发器、冷凝器(若带回热,还有回热器)模型计算获得系统的目标函数,判断该指标

是否达到最优来决定是输出结果还是进入下一步迭代。

2.2 多目标优化数学方法^[2]

本研究从技术和经济两方面的要求出发,以系统焓效率 η_{ex} 大、净输出比功 w_{net} 大、 UA 值小、膨胀机出口工质的体积流量 $q_{v,out}$ 小 4 个指标为目标函数,对 中低温余热发电有机朗肯循环系统进行多目标优化求解。

目标函数:

Max: η_{ex}, w_{net}

Min: $UA, q_{v,out}$

根据多目标优化理论,上述最优化问题可转化为:

Max: $f_1 = w_{net} / UA$

Max: $f_2 = \eta_{ex} / q_{v,out}$

采用线性加权评价函数法对以上包含两个目标函数的最优化模型进行求解,加权系数由文献 [15] 中提到的 α 方法确定,即:

评价函数:

$$VF = \varphi f_1 + \psi f_2 \tag{6}$$

其中,

$$\varphi = \frac{f_2^1 - f_2^2}{(f_1^1 - f_1^1) + (f_2^1 - f_2^2)} \tag{7}$$

$$\psi = \frac{f_1^2 - f_1^1}{(f_1^2 - f_1^1) + (f_2^1 - f_2^2)} \tag{8}$$

式中: φ, ψ —加权系数; f_1^1, f_2^2 —目标函数 f_1 和 f_2 的最大值; f_1^2 (或 f_2^1)—在目标函数 f_2 (或 f_1) 取得最大值时目标函数 f_1 (或 f_2) 的函数值。

2.3 蒸发器的热力计算

在超临界工况下,蒸发器内发生的是变温换热过程,因此其蒸发器的热力计算应区别于亚临界工况。

在超临界工况下,如果假设冷、热流体比热容保持不变,此时,以常用方法确定的蒸发器效能存在一定的误差。图 4 为不同压力下工质 R152a 的比热容随温度的变化关系曲线。由图可以发现,当临界温度在 113.26 °C 附近时, R152a 的比热容随温度变化的幅度非常大,因而这种方法已不再适用于超临界工况下蒸发器的模型计算。同样,利用对数平均温差(LMTD)方法和 $\epsilon - NTU$ 方法对超临界工况下蒸发器模型的计算结果也存在一定的偏差。但值得说明的是,对于超临界 ORC 系统中回热器、冷凝器的计算,由于工质 R152a 的比热容在温度低于 85 °C 时随温度的变化很小,在误差允许的范围内,这种方

法仍旧是适用的。

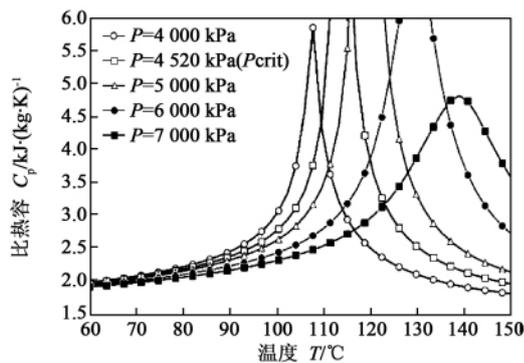


图 4 不同压力下 R152a 比热容随温度的变化关系曲线

Fig. 4 Specific heat capacity of R152a vs. temperature at various pressures

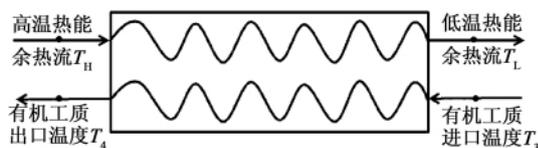


图 5 蒸发器示意图

Fig. 5 Schematic diagram of an evaporator

为了更接近实际情况,同时考虑到焓差既能表示换热量又可以表示效能,蒸发器内两侧流体之间的传热量用焓差表示,图 5 为蒸发器示意图,根据热平衡关系式,有:

$$Q_{\text{evap}} = q_m (h_3 - h_4) = q_{m,H} (h_H - h_L) \quad (9)$$

其中 $q_{m,H}$ 表示余热烟气流量。对于理想换热器,下面两种情况哪种会发生取决于回热器中两股流体哪股有较小的比热容。两种情况为: T_1 趋近于 T_H , T_L 趋近于 T_8 ; 蒸发器的最大换热量 Q_{max} 为下面两个换热量中的较小值^[16]:

$$Q = q_{m,H} (h_H - h'_L) \quad (10)$$

$$Q = q_m (h'_1 - h_8) \quad (11)$$

式中: h'_L —假设 $T_L = T_3$ 条件下的比焓; h'_1 —假设 $T_4 = T_H$ 条件下的比焓。

据此,蒸发器的效能 ε 可表示为:

$$\varepsilon = \frac{q_{m,H} (h_H - h_L)}{Q_{\text{max}}} = \frac{q_m (h_4 - h_3)}{Q_{\text{max}}} \quad (12)$$

以蒸发压力为 4 520 kPa、最高温度为 140 °C、最低温度为 35 °C,并以 R152a 为工质的带回热器的超临界有机朗肯循环计算为例。根据一般方法计算的热效率为 47.93%,由本文参考文献 [16] 给出的方法计算的热效率为 11.72%,而在该温度之间

的卡诺循环热效率仅为 25.41%。可见,假设比热容不变,常用方法计算的结果是不可靠的,而本计算的结果是相对合理的。

3 结果与分析

以 R152a 为循环工质,采用图 2 所示的动力循环,利用 EES 软件编程方法对超临界工况下 ORC 系统进行计算和分析。研究工况为:余热烟气入口温度 150 °C,体积流量 4 000 m³/h,冷却水入口温度 25 °C;计算超临界动力循环的蒸发压力范围为 4 520 ~ 5 500 kPa。

3.1 热效率

图 6(a) 为在有、无回热器两种情况下系统热效率随蒸发压力的变化关系曲线。两种情况下系统最大热效率分别为 11.72% 和 11.07%,较黄晓艳等人计算的结果(12.22%)略小^[17],这主要是由于所用的热源温度(150 °C)比他们的热源温度(200 °C)低了 50 °C。

图中在蒸发压力 4 520 ~ 5 500 kPa 范围内:(1)带回热器时,热效率随蒸发压力的增大而减小,当余热流体变化引起蒸发压力波动时,系统热效率受蒸发压力的影响较大,这与 Gu W 等人的研究结果一致^[18];(2)在不带回热器的情况下,系统热效率随蒸发压力的增大先小幅增大后缓慢减小,存在最佳工况点;随着蒸发压力的继续增大,系统热效率受蒸发压力的影响较大,开始显著降低;这是因为随着蒸发压力的增加,泵所消耗的功占膨胀机输出功的比例显著提高。

图中所示,不带回热器时系统最大热效率(11.07%)对应的蒸发压力为 5 014 kPa,而带回热器时其最大热效率(11.72%)对应的蒸发压力仅为 4 520 kPa,与前者相比降低了 494 kPa(接近 5 个大气压);可见,增加回热器不仅能够有效地提高系统热效率,还能在保证较高热效率的同时选择较低的蒸发压力。

3.2 炯效率

图 6(b) 为在有、无回热器两种情况下系统炯效率随蒸发压力的变化关系曲线。两种情况下,系统炯效率随蒸发压力的变化趋势一致,均随蒸发压力的增大而减小。Tetelbaum 及 Gu Zhaolin 等人指出超临界有机朗肯循环系统的炯效率最高可达 50% 以上^[19~20];由于所选用的工质不同,且回收余热的热源温度仅为 150 °C,因此本研究的最大炯效率只

能达到 41.42%。

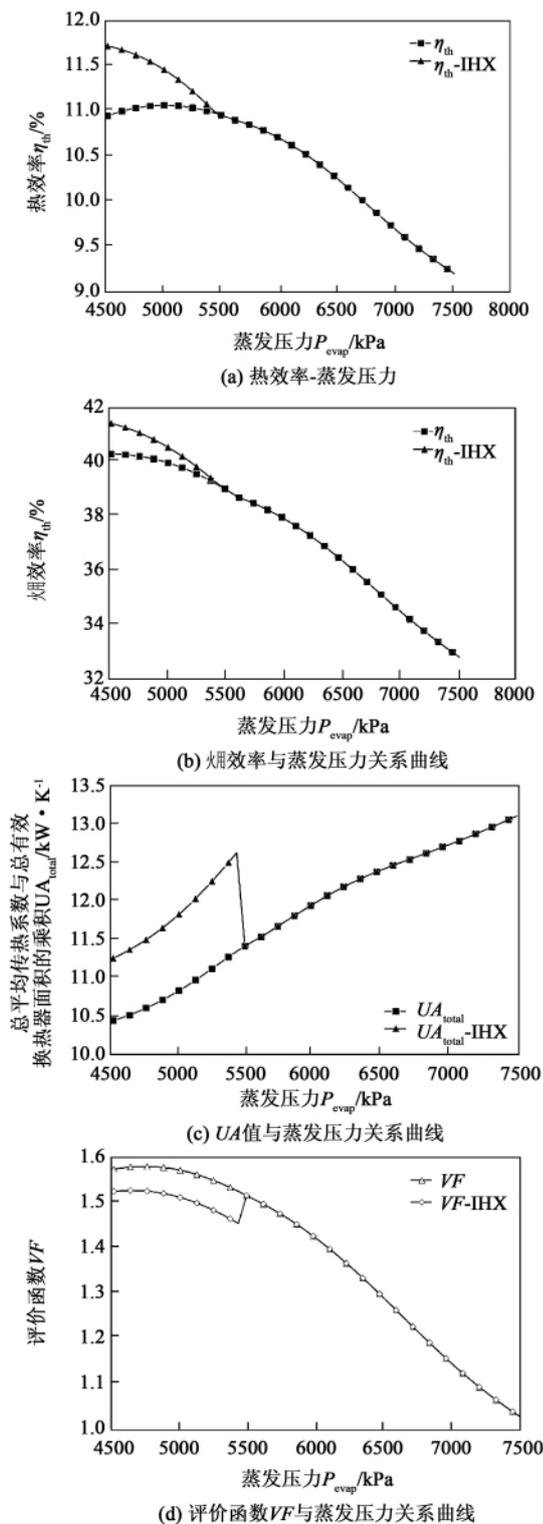


图 6 在有、无回热器两种情况下 ORC 系统性能随蒸发压力的变化关系曲线

Fig. 6 Performance of the ORC system vs. evaporation pressure under both conditions of having or not recuperators

由图可见 在 4 520 kPa 的蒸发压力下 增加回热器后系统热效率(41.42%) 仅比不带回热器时的热效率(40.29%) 提高了 1.13% ,增加幅度仅为 2.8%;可见 系统增加回热器后能够提高系统热效率 但是提高的幅度有限。

3.3 UA 值

UA 值是换热器总平均传热系数与总有效传热面积的乘积。图 6(c) 为有、无回热器两种情况下系统 UA 值随蒸发压力的变化关系曲线。从图中可以发现 在蒸发压力 4 520 ~ 5 500 kPa 范围内 增加回热器后 UA 值增加了 810 ~ 1 290 W/K ,增幅最高可达 11.4%;这主要是因为回热器中进行的是汽-液换热(回热器一侧是膨胀机出口的工质乏汽,另一侧为从加压泵来的液态有机工质) ,换热系数不高 同时换热温差不大 因而系统总传热面积大幅增加 从而导致 UA 值的显著增加。

3.4 多目标优化指标

从技术和经济两方面的要求出发 基于 2.2 节建立的多目标优化数学模型 获得了超临界 ORC 系统的评价函数 VF 随蒸发压力的变化关系曲线(如图 6(d) 所示) 。由图可知 增加回热器后系统评价函数 VF 值略有降低 这是由于增加回热器后系统总的传热面积增加将导致设备总投资增加。

从图中还可以发现 在有、无回热器两种情况下评价函数 VF 均随蒸发压力的增大先增加后减小 存在最佳的工况点; 不带回热器时对应最大 VF 值(1.581) 的蒸发压力为 4 972 kPa ,而带回热器时对应最大 VF 值(1.528) 的蒸发压力为 4 654 kPa ,与前者相比蒸发压力降低了 318 kPa(约三个大气压) ;可见 增加回热器后最佳工况点的蒸发压力降低 从而降低了对设备系统强度、密封性等方面的要求。

4 结 论

本研究基于超临界有机朗肯循环的低温余热发电系统模型 采用 EES 软件进行计算和分析 探讨了增加回热器对 ORC 系统性能的影响 并获得以下结论:

- (1) 对于大部分有机工质 在临界点附近其比热容随蒸发压力的变化显著 在超临界动力循环的热力计算中应予以考虑;
- (2) 超临界 ORC 系统中 增加回热器后能够有效提高系统热效率 同时降低对应系统最大热效率时的蒸发压力; 在超临界工况下 系统热效率受蒸发

压力波动影响较大;

(3) 在有、无回热器两种情况下,系统焓效率均随蒸发压力的增大而减小;增加回热器后能够提高系统焓效率,但是提高的幅度不大;

(4) 多目标优化研究表明,带回热器时系统最佳工况点为蒸发压力 4 654 kPa,比无回热器时降低了 318 kPa;在超临界 ORC 系统中,增加回热器还可以降低对设备系统的强度和密封性等方面的要求。

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(辉 编辑)

双油路离心喷嘴雾化特性试验 = **Experiment of the Atomization Characteristics of a Dual-oil-line Centrifugal Nozzle** [刊 汉] LIU Cun-xi ,XING Shuang-xi ,FANG Ai-bing ,XU Gang(Engineering Thermophysics Research Institute ,Chinese Academy of Sciences ,Beijing ,China ,Post Code: 100190) //Journal of Engineering for Thermal Energy & Power. - 2013 28(1) . - 33 ~37

Experimentally studied were the atomization characteristics of a whole set of 6 dual-oil-line nozzles of an engine by using a LSA-III type laser particle size meter ,including the oil supply characteristics of the main and auxiliary oil line ,atomization cone angle ,Sauter mean particle diameter(SMD or d_{32}) and the dimension distribution. The research results show that the total non-uniformity coefficients of the mass flow rates of the main and auxiliary oil line are 2.42% and 3.29% respectively. The atomization cone angle and mean particle diameter will decrease and the absolute value of the slope will gradually become smaller with an increase of the oil supply pressure after the atomization cone angles of the main and auxiliary oil line have been fully developed. The development process of the atomization cone of the central auxiliary oil line was analyzed at a low oil supply pressure. The atomization cone angle will quickly become bigger and the mean particle diameter will rapidly become smaller with an increase of the oil supply pressure. **Key words:** dual-oil-line centrifugal nozzle ,atomization characteristics ,atomization cone angle ,average particle diameter

CO₂ 跨临界热泵和加热炉冷却循环耦合系统性能分析 = **Analysis of the Performance of a Transcritical Carbon Dioxide Heat Pump and Heater Cooling Cycle Coupled System** [刊 汉] WANG Hong-li ,LIU Jian-xiong ,ZHANG Yan ,CHEN Bin(College of Metallurgy and Energy Source ,Hebei United University ,Tangshan ,China ,Post Code: 063009) //Journal of Engineering for Thermal Energy & Power. - 2013 28(1) . - 38 ~41

Presented was the waste heat recovery of a heater realized by using a transcritical carbon dioxide heat pump coupled with the Rankine cycle. By adopting the thermodynamic method ,the key parameters influencing the efficiency of the coupled cycle and the performance of the transcritical carbon dioxide heat pump were studied respectively. With an increase of the COP of the heat pump ,the efficiency of the coupled cycle will go up. After the performance parameter of the heat pump has exceeded its limit value ,the bigger the power consumption ratio of the compressor ,the lower the efficiency of the coupled cycle. Within the exhaust gas pressure range of the heat pump ,both COP of the heat pump and the efficiency of the coupled cycle have their limit values. Under the given conditions ,the optimum exhaust gas pressure is regarded as 8.5 MPa ,the COP as 4.2 and the efficiency of the coupled cycle as 0.35. To raise the evaporation temperature or to lower the condensing temperature can enhance the performance of the heat pump and the efficiency of the coupled cycle. The foregoing can offer a theoretical basis for recovering the waste heat of a heater and enhancing the efficiency of a power plant. **Key words:** transcritical carbon dioxide heat pump ,Rankine cycle ,coupled cycle ,performance analysis ,thermodynamic method

超临界工况下回热器对低温余热发电系统的性能影响 = **Influence of a Recuperator on the Performance of Its Low Temperature Waste Heat Power Generation System Under the Supercritical Operating Condition**

[刊,汉]JIANG Liang ,XU Jian ,ZHU Ya-dong ,YU Li-jun(College of Mechanical and Power Engineering ,Shanghai Jiaotong University ,Shanghai ,China ,Post Code: 200240) //Journal of Engineering for Thermal Energy & Power. - 2013 28(1) . - 42 ~ 47

To study the influence of a recuperator additionally installed in a low temperature waste heat power generation system on the performance of the system under the supercritical operating condition ,established was a supercritical organic Rankine cycle calculation model. It has been noted that the thermal parameters of the organic Rankine cycle calculated under the supercritical operating condition by using the common methods have certain deviations. By employing the EES(engineering equation solver) software ,the thermal parameters of the system with and without a recuperator were calculated. The research results show that with R152a serving as the working medium and under the supercritical operating condition ,the maximal thermal efficiency of the system after a recuperator has been additionally mounted can increase by 0. 65% and the corresponding evaporation pressure can go down by 494 kPa. The exergy efficiency of the system can somehow increase ,however ,such an increment has its limits. It has been found through a multi-target optimization that after an additional installation of a recuperator ,the evaporation pressure of the system under the optimum operating condition is 4654 kPa and down by 318 kPa when compared with the case without a recuperator. **Key words:** low temperature waste heat power generation ,supercritical ,organic Rankine cycle ,recuperator ,multi-target optimization

考虑环境影响的有机朗肯循环系统性能研究 = **Study of the Performance of an Organic Rankine Cycle System with the Environment Influence Being Considered** [刊,汉]ZHANG Chun-hui ,ZHANG Xin-ming ,DING Cong-an(Education Ministry Key Laboratory on Low-grade Energy Source Utilization Technology and System ,College of Power Engineering ,Chongqing University ,Chongqing ,China ,Post Code: 400030) ,HONG Guang(Urban Construction Research Institute ,Beijing ,China ,Post Code: 100120) //Journal of Engineering for Thermal Energy & Power. - 2013 28(1) . - 48 ~ 52

To comprehensively evaluate the environmental protection and thermal cost-effectiveness performance of a sub-critical organic Rankine cycle system ,on the basis of an analysis of the cyclic performance of the system ,the exergy parameter was used to quantify the environment influence of the working medium with a model for evaluating the environment influence of an organic Rankine cycle system and a comprehensive evaluation index being presented. Furthermore ,the authors have also compared and analyzed the rationality of a sustainability coefficient to serve as an index to evaluate the overall performance of an organic Rankine cycle system. Finally ,the influence of the parameters of a system on the cyclic performance was studied through a practical case. It has been found that the ORC system can save standard coal by 6.42×10^6 kg/a and reduce equivalent CO₂ emissions by 1.26×10^7 kg/a. The sustainability coefficient of the system has a maximum value with an increase of the temperature at the inlet of the expander. It has been noted that the working medium R124 and R600a are the relatively good choice with the environment protection and cyclic performance etc. factors being considered in a comprehensive way. **Key words:** low grade energy source ,organic Rankine cycle ,environment influence ,sustainability ,waste heat power generation