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CO_2 跨临界双级压缩带回热器与不带回热器循环分析

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摘 要: 基于氟利昂制冷剂的 ODP(臭氧层破坏势) 和 GWP(温室效应) 问题,运用热力学方法,对 CO_2 跨临界双级压缩带回热器循环 TSCV + TGC + IHX 与不带回热器循环 TSCV + TGC 建立了数学模型,并基于 Visual Basic 程序基础,开发了两种双级循环性能分析平台。结果表明,相同对比条件下,循环 TSCV + TGC + IHX 平均性能比循环 TSCV + TGC 高 5% ~10% ,最优中间压力比循环 TSCV + TGC 低约 5% ~15% 。本研究为高效、节能的 CO_2 跨临界循环热泵热水器产品的开发提供了基础资料。

关 键 词: 热力学; CO_2 跨临界双级循环; 回热器; 性能分析; 热泵热水器

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引 言

随着氟利昂制冷剂的臭氧层破坏和温室效应问题日益突出,开展环境友好性的自然工质 CO_2 替代工作具有重要意义[1]。CO_2 跨临界循环放热特点是排气温度高、温度滑移大、气体冷却器出口温度低和系统性能好等特点,其应用于热泵热水器已成为目前热泵领域中研究的热点[2~3]。

CO_2 跨临界单级循环具有运行压力高、节流损失严重及压缩机耗功大等特点[4~5],双级压缩可以减小压缩机耗功和制冷剂泄露,进而提高 CO_2 跨临界循环系统性能,文献[6]分别对 CO_2 跨临界双级循环进行了研究,系统中增设回热器可以进一步优化和提高 CO_2 跨临界循环性能[7~8],这在 CO_2 空气源热泵系统中尤为重要。

以往,CO_2 跨临界循环性能分析多采用国外专用软件,不但使用范围有限,且价格昂贵。基于 Visual Basic 程序软件,本研究分别对 CO_2 跨临界双级压缩带回热器(TSCV + TGC + IHX,Two Stage Cycle with Valve and Two Gas Coolers with Intermediate Heat Exchanger) 和不带回热器(TSCV + TGC,Two Stage Cycle with Valve and Two Gas Coolers) 的两种循环开发了性能计算平台[9~11],并进行了理论分析,为今后开展双级循环性能测试试验台及开发高效 CO_2 热泵热水器产品提供基础资料。

1 CO_2 跨临界双级压缩带回热器与不带回热器的循环组成及热力学分析

1.1 CO_2 跨临界双级压缩带回热器与不带回热器的循环组成

CO_2 跨临界双级压缩不带回热器循环 TSCV + TGC 和带回热器循环 TSCV + TGC + IHX 系统主要包括高(低) 压级压缩机、高(低) 压级气体冷却器(或中间回热器) 、节流阀、蒸发器。

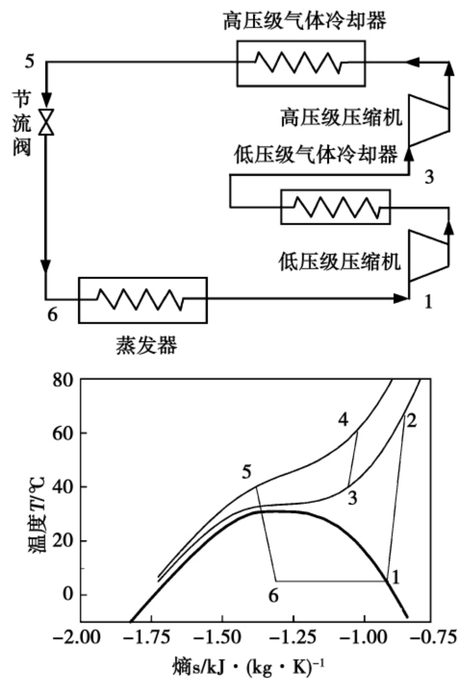

图 1 CO_2 跨临界双级循环 TSCV + TGC 原理图和 $T-s$ 图

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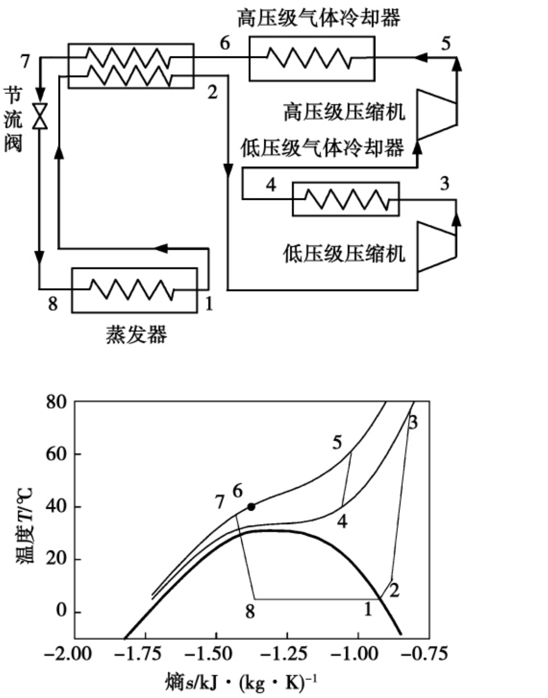


图 2　CO_2 跨临界双级压缩带回热器循环 TSCV + TGC + IHX 原理图和 $T-s$ 图

CO_2 跨临界双级循环 TSCV + TGC + IHX 工作过程与双级循环 TSCV + TGC 基本相同,只是高压高温气态制冷剂在高压级气体冷却器内定压放热后,在中间回热器内进一步过冷,经蒸发器定压吸热的制冷剂再回到中间回热器,与来自高压级气体冷却器的制冷剂进行换热,使进入低压级压缩机的制冷剂过热,从而完成了一个完整循环。

图 1 和图 2 分别给出了双级循环 TSCV + TGC 和 TSCV + TGC + IHX 原理图和对应的 $T-S$ 图。

1.2　CO_2 跨临界双级压缩带回热器与不带回热器循环热力学分析

1.2.1　CO_2 跨临界双级压缩不带回热器循环 TSCV + TGC

制冷性能系数:

$$COP = \frac{h_1 - h_6}{(h_2 - h_1) + (h_4 - h_3)} \tag{1}$$

制热性能系数:

$$COP = \frac{(h_2 - h_3) + (h_4 - h_5)}{(h_2 - h_1) + (h_4 - h_3)} \tag{2}$$

1.2.2　CO_2 跨临界双级压缩带回热器循环 TSCV + TGC + IHX

制冷性能系数:

$$COP = \frac{h_1 - h_8}{(h_3 - h_2) + (h_5 - h_4)} \tag{3}$$

制热性能系数:

$$COP = \frac{(h_3 - h_4) + (h_5 - h_6)}{(h_3 - h_2) + (h_5 - h_4)} \tag{4}$$

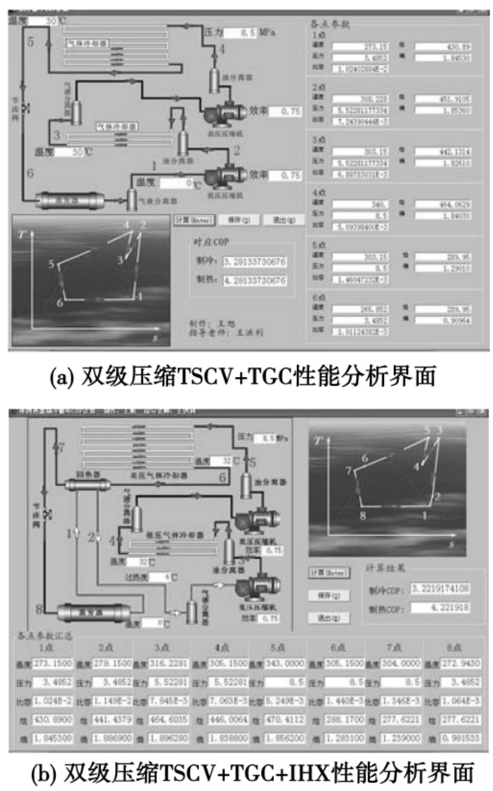
式中: h_1、h_2、h_3、h_4、h_5、h_6、h_8—循环中各点焓值。

计算条件和假设: (1) 系统在稳态条件下运行; (2) 忽略换热器及其它管道压降和热损失; (3) 高、低压级压缩机效率设为 0.75; (4) 蒸发温度范围设为 -5 ~ 5 ℃; (5) 两个气体冷却器出口温度为 32 ~ 42 ℃; (6) 蒸发器过热度设为 5 ~ 10 ℃。

2　CO_2 跨临界双级压缩带回热器与不带回热器循环计算平台的开发及性能分析

2.1　CO_2 跨临界双级压缩带回热器与不带回热器循环计算平台的开发

以往,CO_2 跨临界循环性能分析多采用购买的国外专用软件,不但使用范围有限,且价格昂贵。本项目采用通用软件 Visual Basic 对两种 CO_2 跨临界双级循环进行了性能分析,并开发了性能计算软件平台,可为相关研究提供基础资料。



(a) 双级压缩TSCV+TGC性能分析界面

(b) 双级压缩TSCV+TGC+IHX性能分析界面

图 3　CO_2 跨临界双级压缩 TSCV + TGC 和 TSCV + TGC + IHX 性能分析界面

图 3 分别给出了基于 VB 软件编制的 CO_2 跨临

界双级循环 TSCV + TGC 和循环 TSCV + TGC + IHX 性能测试软件平台分析界面。

2.2 CO_2 跨临界双级压缩带回热器与不带回热器循环性能分析

2.2.1 压力和效率对 CO_2 跨临界双级循环性能影响

在 CO_2 跨临界双级循环中，对应每一个高压工况都具有一个最优中间压力，从而使系统 *COP* 最大。给定计算条件：蒸发温度 $t_e = 0$ ℃，冷却温度 $t_c = 35$ ℃，过热度 $t_{sh} = 10$ ℃和高压级压缩机排气压力为 8.5 MPa。图 4 给出了双级循环 *COP* 随中间压力的变化情况。循环 TSCV + TGC 最优中间压力为 7.2 MPa，最大系统 *COP* 为 2.72；循环 TSCV + TGC + IHX 最优中间压力为 6.8 MPa，最大 *COP* 为 2.82。相同条件下，循环 TSCV + TGC + IHX 性能最优，且循环 TSCV + TGC + IHX 对应的最优中间压力要低于循环 TSCV + TGC，这在压缩机选型和减小系统泄漏等方面具有一定优势。

图 4 也给出了理想情况下两种双级循环 *COP* 随中间压力变化，其中，高、低压级压缩机效率均取 100%，两种情况下各个循环对应的最优中间压力分别基本相同。实际上，这种理想情况是不存在的。

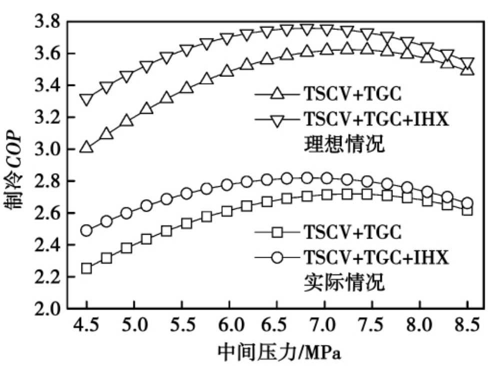


图 4　*COP* 随中间压力的变化

图 5 给出了高压为 8.5 MPa，高、低压级压缩机效率分别为 0.75 和 0.6 时，两种循环 *COP* 随中间压力的变化。与图 4 相比，低压级压缩机效率降低后，循环 *COP* 和相应的最优中间压力都有所降低，分别为：循环 TSCV + TGC 最优中间压力为 6.4 MPa，最大 *COP* 为 2.29；循环 TSCV + TGC + IHX 最优中间压力为 5.6 MPa，最大 *COP* 为 2.41。相同条件下，循环 TSCV + TGC + IHX 性能要优于循环 TSCV + TGC；高压级压缩机效率降低后，两个循环 *COP* 都有所降低，但相应的最优中间压力却都呈增加趋势，分别为：循环 TSCV + TGC 最优中间压力为 7.9 MPa，最大系统 *COP* 分别为 2.65；循环 TSCV + TGC + IHX 最优中间压力为 7.7 MPa，最大 *COP* 为 2.72。相同条件下，循环 TSCV + TGC + IHX 性能仍优于循环 TSCV + TGC 性能。

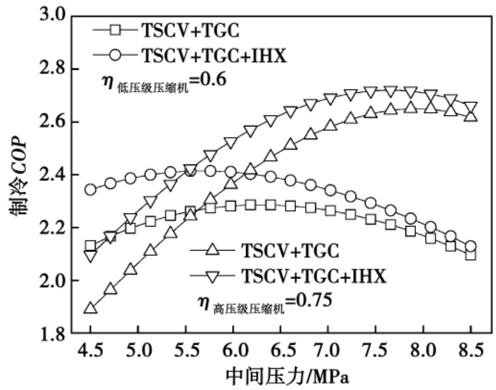


图 5　*COP* 随中间压力和压缩机效率的变化

分析表明，低压级压缩机的效率对整个循环系统的性能影响更为显著，这在 CO_2 跨临界双级循环中，低压级压缩机的设计、选型和工况调节等诸多方面提供理论依据。

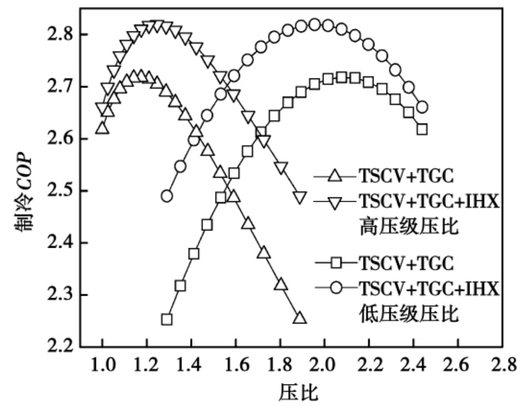


图 6　*COP* 随循环压比的变化

图 6 分别给出了高压为 8.5 MPa 时，各个循环 *COP* 随高、低压级压缩机压比变化情况。在整个压比变化范围内，每个循环都存在一个最优压比，使得在此压比下系统 *COP* 最大。当压缩机压比很大或很小时，循环均不能达到最优工况，系统性能较低。

两个循环最优低压级压比情况分别为：循环 TSCV + TGC 最优压比为 2.1，最大系统 *COP* 为 2.72；循环 TSCV + TGC + IHX 最优压比为 2.0，最大 *COP* 为 2.82。相同条件下，循环 TSCV + TGC 最优

压比较低,这在调节系统运行工况、减小系统泄漏方面具有一定优势。系统 *COP* 随高压级压比变化关系,可参照低压级压比方法分析。

2.2.2　蒸发温度对两种 CO_2 跨临界双级循环性能影响

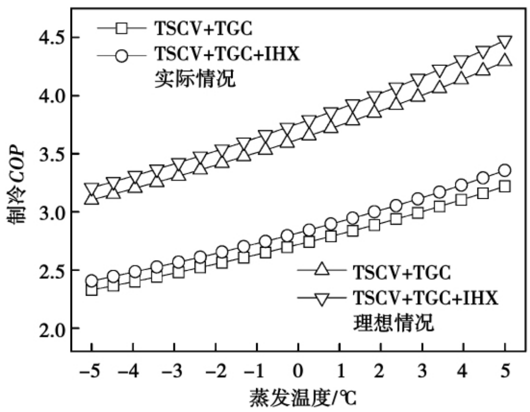


图 7　双级循环 *COP* 随蒸发温度变化

图 7 给出了两种双级循环 *COP* 随蒸发温度的变化情况。在蒸发温度变化范围内,所有循环的性能都随蒸发温度的增加而提高。其中,循环 TSCV + TGC + IHX 性能较好。

图 7 也给出了理想情况下循环 *COP* 随蒸发温度的变化。与实际循环相比,理想循环的性能要更优,在整个蒸发温度变化范围内,理想情况循环 *COP* 与实际循环 *COP* 随蒸发温度变化趋势基本一致。

2.2.3　气体冷却器出口温度对两种 CO_2 跨临界双级循环性能影响

气体冷却器内的换热是在 CO_2 超临界区内进行的,这与普通制冷剂的放热不同。因此,研究超临界区内 CO_2 放热机理是有必要的,同时这也是提高整个循环性能的主要研究方向[12]。

当低压级气体冷却器出口温度为 40 ℃,高压级气体冷却器出口温度从 32 ℃变化到 42 ℃时,图 8 分别给出了两种双级循环 *COP* 和最优中间压力随气体冷却器出口温度的变化。

由图 8 可知,两种循环的性能都随气体冷却器出口温度的增加而降低。其中,循环 TSCV + TGC + IHX 性能较优,循环 TSCV + TGC 性能较差。在气体冷却器出口温度变化范围内,循环 TSCV + TGC + IHX 和循环 TSCV + TGC 性能相差趋势比较一致。在气体冷却器出口温度范围内,两种循环的最优中间压力都随气体冷却器出口温度的增加而增加。其中,循环 TSCV + TGC 的最优中间压力较高,循环 TSCV + TGC + IHX 最优中间压力较低。

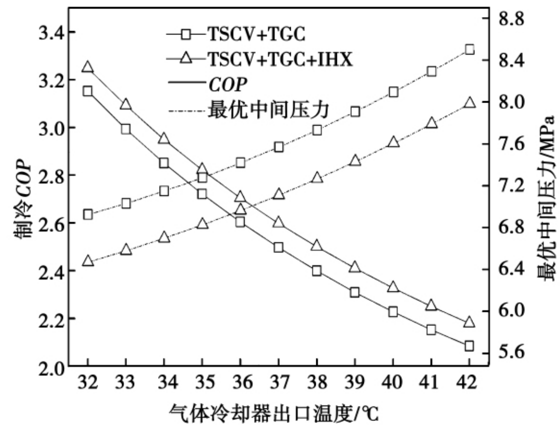


图 8　双级 *COP* 和中间压力随冷却温度的变化

另外,用膨胀机代替节流阀可以提高 CO_2 跨临界循环性能,由于 CO_2 专用膨胀机加工精度高和暂时缺少设计经验,因而用双级循环提高 CO_2 跨临界循环效率更可行。

3　结　论

本研究开发了 CO_2 跨临界双级压缩带回热器循环 TSCV + TGC + IHX 与不带回热器循环 TSCV + TGC 程序计算平台,并进行了循环性能分析。

(1) 在蒸发温度或气体冷却器出口温度范围内,CO_2 跨临界双级循环 TSCV + TGC + IHX 性能均优于双级循环 TSCV + TGC;

(2) 循环 TSCV + TGC + IHX 平均性能比循环 TSCV + TGC 高约 5% ~ 10%,最优中间压力比循环 TSCV + TGC 低约 5% ~ 15%,这在压缩机选型、减小系统泄漏等方面具有一定优势;

(3) 鉴于 CO_2 膨胀机加工精度高和暂时缺少设计经验,用双级循环提高 CO_2 跨临界循环效率更可行。

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（编辑　伟）

新技术、新设计

涡轮级喷嘴叶片上液膜形成的研究

《Теплоэнергетика》2010 年 9 月号提供了在蒸汽低湿度区域内涡轮喷嘴叶片表面上液膜厚度试验测定的结果，这可以预测液膜形成和汽化的部位，进而预测在喷嘴叶片表面腐蚀过程发展的区域。

研究的结论为:

(1) 在叶片前平均的初始湿度 $y_0 = 1.2\%$ 时，在大扇形度涡轮级喷嘴叶片上形成液膜，其厚度不超过 150 μm.

(2) 在来流的流入角改变时，在叶片的进汽边和出汽边区域内液膜厚度发生最大变化。

(3) 液膜厚度沿叶型周边以及在沿叶片高度不同截面内的分布是很不均匀的。

(4) 在一些测量传感器上面液膜没有被证实，在叶片前的平均湿度 $y_0 = 1.2\%$ 时，在所研究喷嘴叶栅叶片的表面上没有形成连续的液膜。

(5) 在所研究喷嘴叶片表面上的工质和饱和温度之间的差别 ΔT_c 发生本质的变化。例如，如果在叶背上实际的所有点的 $\Delta T_c > 0$，那么在叶盆上大多数点的 ΔT_c 明显低于零。

（吉桂明　摘译）

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In the light of an error accumulation problem of the LPV (linear parameter varying) model, an improved LPV model was put forward. On the basis of a nonlinear model for a turbofan engine, a LPV model for the turbofan engine was established with its LP rotor rotating speed serving as a scheduling variable. A rotating speed-oil supply quantity feedback was added to the model in question. Together with a PI link, a closed loop circuit was formed, achieving an improvement of the LPV model. The simulation results show that the improved LPV model in question can effectively overcome the error accumulation defect of the LPV model, thus more realistically reflecting the steady and dynamic state characteristics of nonlinear models. **Key words**: aeroengine, gain scheduling, linear parameter varying model, PID (proportional, integral and differential)

双压凝汽器闭式循环水系统的最优运行方式 = Optimal Operation Mode of a Dual-pressure Condenser Closed Type Circulating Water System [刊,汉] ZENG De-liang, WANG Wei, LIU Ji-zhen (College of Control and Computer Engineering, North China University of Electric Power, Beijing, China, Post Code: 102206), ZHANG Zhi-gang (Datang International Tianjin Panshan Power Plant, Tianjin, China, Post Code: 301900) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –171 ~ 175

Circulating water inlet temperature is regarded as an important parameter for determining the optimal operation mode of a circulating water pump. For an open type circulating water system, the circulating water inlet temperature represents the ambient temperature. For a closed type one, however, it denotes the cooling tower outlet water temperature. With a counterflow type cooling tower serving as an object of study, in combination with the heat balance calculation formulae for a cooling tower and by adopting an iterative calculation method, the tower outlet water temperatures under different operation modes were determined. In the meantime, a soft method for measuring the tower ingoing air speed was presented. In the earlier literatures, however, the tower ingoing air speed was invariably obtained by an aerodynamic calculation. The problem concerning the multiple solutions to the nonlinear equation in the calculation of the tower outgoing water temperature and ingoing air speed was expounded. A real solution coincident with the physical meaning was finalized. At last, the solution such obtained was applied in the dual-pressure condenser. The optimal operation mode obtained therefrom for the circulating water pumps can serve as a guide for on-site operations. **Key words**: tower ingoing air speed, tower outgoing water temperature, dual-pressure condenser, optimal operation

CO_2 跨临界双级压缩带回热器与不带回热器循环分析 = Analysis of a CO_2 Trans-critical Dual-stage Compression Cycle With and Without a Recuperator [刊,汉] WANG Hong-li, TIAN Jing-rui (College of Metallurgy and Energy Source, Hebei United University, Tangshan, China, Post Code: 063009), MA Yi-tai (Thermal Energy Research Institute, Tianjin University, Tianjin, China, Post Code: 300072) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –176 ~ 180

To address the ODP (Ozone Depletion Potential) and GWP (Global Warming Potential) problems arisen from freon refrigeration coolant, mathematical models were established for CO_2 trans-critical dual-stage compression cycle with a recuperator (TSCV + TGC + IHX) and without a recuperator (TSCV + TGC) by employing a thermodynamic method. In addition, based on Visual Basic program, a platform for analyzing the performance of both cycles was developed. It has been found that under the identical contrast conditions, the average performance of TSCV + TGC

+ IHX is 5% ~10% higher than that of TSCV + TGC and the optimum intermediate pressure of TSCV + TGC + IHX is about 5% ~15% lower than that of TSCV + TGC. The research findings can serve as basic data for development of high efficiency and energy-saving CO_2 heat pump hot water heater products operating in trans-critical cycles. **Key words**: thermodynamics, CO_2 trans-critical dual-stage cycle, recuperator, performance analysis, heat pump hot water heater

高温相变蓄热器数值模拟与实验研究 = Numerical Simulation and Experimental Study of a High Temperature Phase-change Heat Accumulator [刊，汉] WU Bin, XING Yu-ming (College of Aeronautical Science and Engineering, Beijing University of Aeronautics and Astronautics, Beijing, China, Post Code: 100191) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –181 ~185

A High Temperature Phase-change Heat Accumulator constitutes a key component in a space solar energy thermal power generation system, of which the heat accumulation in the phase-change material (PCM) is regarded as a key technology. A ground surface experiment was performed of a heat accumulation system with LiF-CaF_2 serving as the PCM and dry air as a working medium. On this basis, the mathematical models were established respectively for the heat accumulation unit tubes filled with pure PCM and FCPCM (foam compound phase-change material) under the corresponding conditions. The numerical calculation results show that the calculated values of the pure PCM heat accumulation unit tubes are in very good agreement with the test ones, proving the validity of the calculation model. In addition, a comparison was made with the calculated value of the heat accumulation unit tubes filled with FCPCM. The comparison result indicates that filling with foam can strengthen the heat transfer performance of the PCM, thereby enhancing the thermal performance of the heat accumulation system. **Key words**: heat accumulator, phase-change material, foam compound phase-change material (FCPCM), thermal performance, phase-change material (PCM) heat transfer

不可逆中冷焦耳—布雷顿功热并供系统㶲分析 = Exergy Analysis of an Irreversible Intercooled Joule-Brayton Power-and-heating Cogeneration System [刊，汉] XU Yi-lin, HUANG Yue-wu (College of Environment Science and Engineering, Donghua University, Shanghai, China, 201620) // Journal of Engineering for Thermal Energy & Power. – 2011, 26(2). –186 ~190

By employing an exergy analytic method of thermodynamics, taken into account respectively were the following factors: thermal resistance losses in high and low temperature side heat exchangers, heat recovery device side heat exchangers and intercoolers, and inner irreversible losses in the compressors and turbines. With the non-dimensional total output exergy and its efficiency serve as the target function and with the aid of a numerical analytic method, studied was the exergy performance of an irreversible intercooled Joule-Brayton power-and-heating cogeneration system with a constant temperature heat source. In addition, the influence of the main characteristic parameters on the non-dimensional total output exergy and its efficiency was also analyzed. The analytic results show that when the intermediate pressure ratio keeps constant but the overall pressure ratio changes, there exist a group of optimum operating parameters making the non – dimensional overall output exergy attain its maximum and also a maximal overall output exergy and efficiency as well as a group of corresponding optimum operating parameters. In such a case, to improve the heat exchange efficiency of the intercoolers can enhance the non – dimensional overall output exergy and efficiency. **Key words**: power and heating cogeneration, intercooling system, total output exergy, exergy efficiency