文章编号:1001-2060(2012)06-0655-05

孔-肋相对位置对通道各壁面换热影响

李广超,吴超林,张 魏,王成军
(沈阳航空航天大学 辽宁省航空推进系统先进测试技术重点实验室,辽宁 沈阳 110136)

摘 要:数值模拟了肋和气膜孔的相对位置对矩形通道4个壁面换热特性的影响,重点分析了通道4个壁面换热系数差别以及3种气膜孔位置换热。计算结果和实验数据吻合较好。结果表明:气膜孔位置对同时带肋和气膜孔的下壁面影响最大,孔在肋间上游换热最好,孔在肋中间换热次之,孔在肋间下游换热最差,气膜孔位置对光滑的左右壁面换热影响较小,对只带肋的上壁面几乎没有影响。肋的扰流和气膜孔抽吸使通道下壁面换热系数增幅最大,左右壁面次之,上壁面最小。沿着流动方向,肋扰流和气膜孔出流共同作用导致带肋壁面换热增强因子先增大后减小,光滑壁面换热增强因子先保持不变后减小。

关 键 词:肋;气膜孔;内冷通道;换热;数值计算

中图分类号:TK472;O242 **文献标识码**:A

引 言

目前,航空发动机涡轮进口温度已经远远超出了材料的耐热极限。可以从研究耐高温的材料以及对涡轮叶片进行有效冷却两方面解决这一问题。冷却主要包括两部分:叶片外部高效气膜冷却降低了燃气的换热温度;叶片内部冷气通过肋扰流、气膜孔抽吸等强化换热方式把传入叶片内部的热量带出叶片。通道加扰流肋可以增大换热面积,增强流体扰动而强化换热,但肋后的低速回流区使换热减弱[1~3]。气膜孔出流的抽吸作用使孔上游边界层变薄,孔下游产生斜冲击流动,换热增强[4~5]。同时带肋和气膜孔壁面(气膜孔位置在相邻肋中间)与单独带肋壁面换热特性接近,带60°肋和气膜孔通道各壁面换热特性差别非常大[6]。气膜孔出流使变截面回转通道中带气膜孔壁面换热增强,不带气膜孔壁面换热减弱。因此,合理布置肋和气膜孔位置可以有效利用二者强化换热优势。

气膜孔在肋间3种不同位置处时通道壁面的换热特性表明,气膜孔布置在肋后低速区可以有效提高换热系数[7],该文献只研究了同时带肋和气膜孔的下壁面换热特性,并没有给出通道其它壁面换热结果。由于只带肋的上壁面在肋后仍存在低速区,下壁面气膜孔出流对上壁面换热规律影响并不清楚;两侧光滑壁面由于受到了上下壁面扰流肋和下壁面气膜孔出流影响,换热特性和光滑通道壁面必然不同。基于此,对孔在肋间3种位置的通道换热特性进行数值模拟,重点分析孔位对各个壁面换热影响以及换热系数沿流动方向的变化。

1 数值计算

1.1 计算方法及模型

利用Fluent提供的分离隐式求解器求解紊流时均运动方程,选用Realizable $k-\varepsilon$ 湍流模型和增强壁面函数,速度和压力的耦合采用simple算法,各参数的离散采用二阶迎风格式,各方程的收敛残差为 $10^{-5} \sim 10^{-7}$。

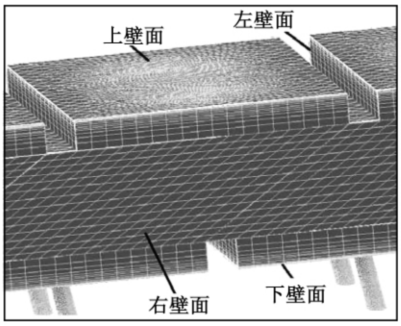


图1 通道结构及网格
Fig.1 Passage structure and mesh

图1给出了孔在肋中间时的模型及网格。通道上下壁面各布置10根肋,且交错布置,通道宽高比为2.5:1。肋与主流方向成90°夹角,肋高与肋宽比为1,肋间距与肋宽比为10:1。气膜孔布置在下壁面,气膜孔长径比为6.1:1,左侧气膜孔出口中心距

收稿日期:2012-03-12; 修订日期:2012-04-01
基金项目:航空科学基金资助项目(2010ZB54004);辽宁省教育厅基金资助项目(L2010425);沈阳航空航天大学青年基金资助项目(201001Y)
作者简介:李广超(1979-),男,辽宁铁岭人,沈阳航空航天大学副教授,博士.

左壁面 7.5 倍气膜孔直径，右侧气膜孔出口中心距右壁面 5 倍气膜孔直径，气膜孔与下壁面夹角为 35°。在通道上下及左右壁面均加了边界层网格，并对上下壁面、气膜孔附近及气膜孔内的网格进行了加密处理，3 种模型的计算网格为 110 万 ~ 140 万，相应的 y^+ 在 1 ~ 10 之间。

1.2 参数定义及边界条件

通道入口雷诺数:

$$Re = \rho_\infty u_\infty d_e / \mu \quad (1)$$

式中: ρ_∞、u_∞—通道入口处流体的密度与平均速度; d_e—通道入口的水力直径; μ—进口温度下流体的运动粘性系数。

气膜孔总出流比:

$$M = (\sum m_i) / m_{inlet} \quad (2)$$

式中: m_i—第 i 对气膜孔出流的质量流量; m_{inlet}—通道进口总质量流量。

努谢尔数:

$$Nu = hd_e / \lambda \quad (3)$$

式中: h—换热系数; λ—流体导热系数。

计算所得数据均处理成换热增强因子 Nu/Nu_0。Nu_0 根据管槽内充分发展的经典实验关联式 $Nu_0 = 0.023 Re^{0.8} Pr^{0.4}$ 计算得出。

通道入口雷诺数为 90000，出流比为 0.22，确定了四壁面恒热流边界条件。

2 计算结果和分析

2.1 计算结果和实验数据对比

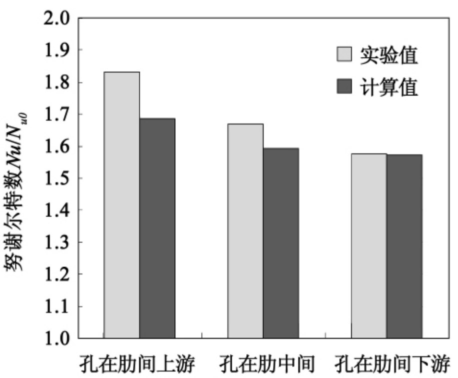


图 2 计算结果和实验数据对比

Fig. 2 Comparison of the calculation results with the test data

图 2 为计算结果与文献 [7] 中实验数据的对比。气膜孔在肋间上游和肋中间时计算结果比试验值小约 10%，气膜孔在肋间下游时计算结果和试验数据非常吻合。这是因为孔在肋间上游和肋中间时，气膜孔出流将肋后低速气体抽出通道来强化换热，数值计算时所选用的湍流模型在计算低速气体时的误差较大。从计算结果和实验数据都可以看出，气膜孔在肋间上游换热最好，在肋中间次之，在肋间下游最差。这是由于气膜孔越靠近上游，孔抽吸效应越大，而随着孔向下游的推移，孔抽吸带来的强化换热作用被肋扰流强化作用所忽略，所以孔越靠近下游，换热越弱。

2.2 气膜孔位置对下壁面换热影响

从图 3(a) 可以看出肋表面换热增强因子最大，之后的高换热区为气膜孔上游 0.5 倍孔径区域与气膜孔下游 1.5 倍孔径之间的区域，换热增强因子为 2.37。两气膜孔之间次之，换热增强因子为 1.97。之后为气膜孔下游较远区域，换热增强因子为1.18。紧靠肋下游 1 倍孔径区域换热被减弱，增强因子只有 0.66。

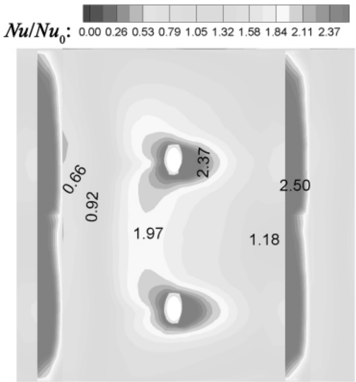
图 3(b) 为气膜孔在肋间下游时换热增强因子分布。气膜孔位于肋后流体再附着区域，与图 3(a) 相比气膜孔上游没有高换热区，其下游大约 1 倍孔径区域，换热增强因子数值较大，但换热区较小; 气膜孔之间区域换热增强因子略小; 肋后换热减弱区大小以及换热增强因子与孔在肋中间位置时相同。这说明气膜孔在肋中间下游位置不能改变肋后换热弱的情况，并且由于气膜孔距下游肋距离小，使气膜孔下游换热增强幅度有限。

图 3(c) 为气膜孔位于肋间上游时换热增强因子分布。气膜孔下游换热增强因子的变化趋势与气膜孔在肋中间相同，但孔下游较远区域以及两孔之间换热增强因子明显大于图 3(a) 和 3(b); 气膜孔布置在肋后回流区，抽吸掉了该区域低速流体，换热得到增强，增强因子为 1.18。

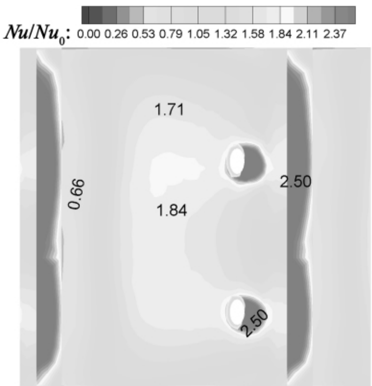
2.3 通道各壁面换热增强因子

在叶片冷却设计过程中，只有知道了通道各个壁面的换热系数，才能够对冷却效果进行精确设计。下面以气膜孔位于肋间上游为例来分析通道各壁面换热差别。对比图 3(c) 和图 4(a) 可以看出上下壁面肋表面换热增强因子相同; 上壁面大部分区域的换热增强因子在 1.4 左右，肋后回流区的换热增强因子在 0.4 左右。上壁面肋间大部分区域换热增强因子小于下壁面相应位置的换热增强因子。上壁面肋间区域换热受肋的影响较大，受气膜孔出流影响较小。通道左右壁面的换热情况基本相同(图 4

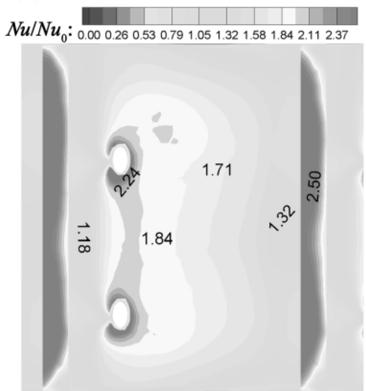
(b)，图 4(c))，换热增强因子在 1.7 左右，大于上壁面，肋后有较小的换热减弱区，换热增强因子为 0.6 左右。这是由于肋和气膜孔使通道内流体剧烈掺混，两侧壁面肋后回流区小于上壁面肋后回流区，整体换热情况较好。



(a) 气膜孔在肋中间



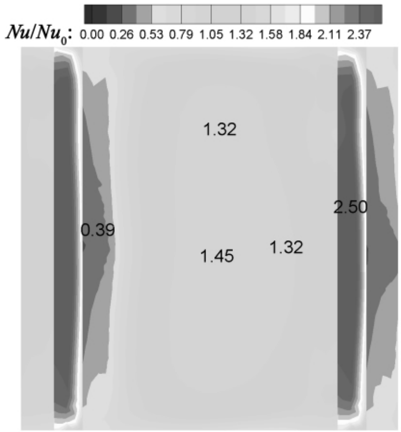
(b) 气膜孔在肋下游



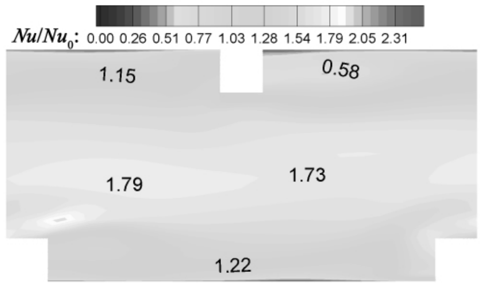
(c) 气膜孔在肋上游

图 3　气膜孔在肋间不同位置处下壁面换热增强因子

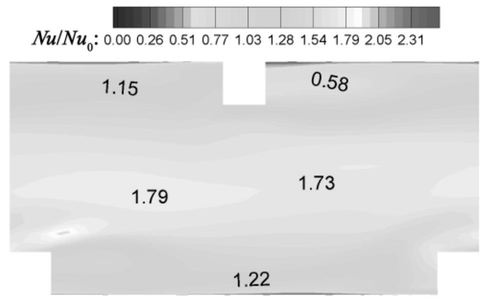
Fig. 3 Heat exchange enhancement factor of the lower wall surface at various locations of the air film hole between ribs



(a) 上壁面



(b) 左壁面



(c) 右壁面

图 4　气膜孔在肋间上游时各壁面换热增强因子分布

Fig. 4 Distribution of the heat exchange enhancement factor on various wall surfaces when the air film holes are located at the upstream between the ribs

2.4　各壁面换热增强因子沿着流向的变化

图 5 为通道各个单元的平均换热增强因子。其中 x 表示从通道进口沿着主流方向距离，l_r 代表肋间距。先分析通道上下壁面。第一根肋前的通道入口段换热增强因子很大。第一根肋到第二根肋之间的区域由于只受到第一根肋的扰流作用，流体之间的掺混较弱，肋和气膜孔强化换热作用不明显，换热增强因子减小；第二根肋后随着扰流肋的增加，流体之间掺混加剧，换热增强因子逐渐增大，第四、五根肋

之间换热强度达到最大值; 之后换热增强因子逐渐减小,这是因为随着气膜孔的出流,通道内流体流量减少,速度降低。

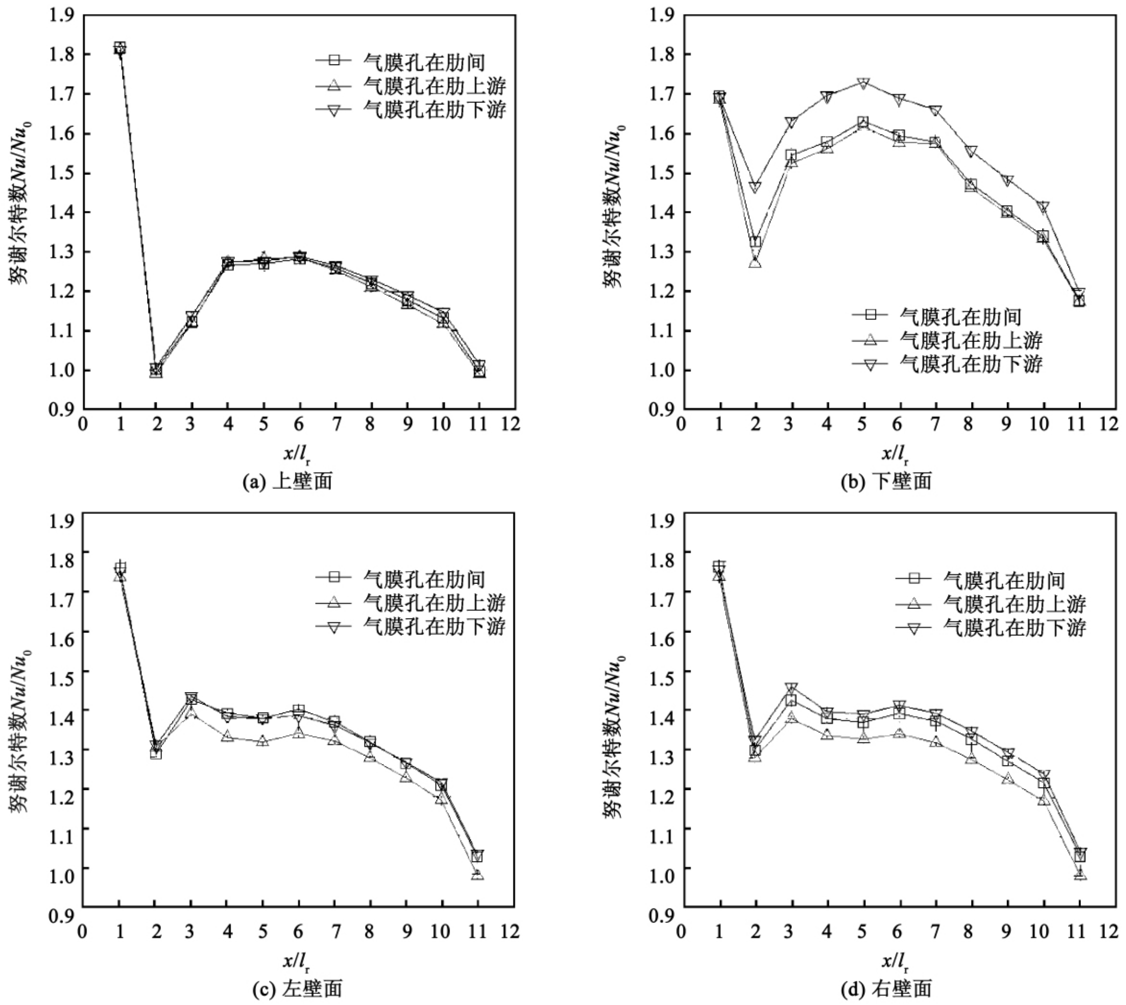


图 5　沿流动方向平均换热增强因子

Fig. 5 Average heat exchange enhancement factor along the flow direction

通道左右壁面,第一根肋前随着边界层的加厚换热增强因子减小; 第一根肋后流体开始扰动,换热增强因子增大; 第二根肋与第五根肋间换热增强因子变化不大,这是因为肋和气膜孔的强化传热与气膜孔出流导致的通道速度降低引起的削弱传热作用相当; 之后气膜孔出流使通道内速度进一步降低,换热增强因子逐渐减小。

分析图 5 的 4 个壁面的换热增强因子可知,气膜孔位置对上壁面换热几乎没有影响。对通道左右壁面换热略有影响,气膜孔在肋间下游换热增强因子较小。气膜孔位置对下壁面换热影响最大,这与图 3(c) 的分析结论是一致的。以上分析说明通道上、左及右壁面主要受肋的扰流和气膜孔出流降低通道速度的影响; 下壁面除了上述两个原因外,还受气膜孔出流抽吸作用影响。

2.5　各壁面平均换热系数

图 6 为气膜孔在肋间不同位置处,通道各壁面的平均换热增强因子。气膜孔位于肋间上游时,各壁面换热增强因子都大于气膜孔位于肋间时相应壁面换热增强因子; 气膜孔在下游时换热增强因子最小。在 3 种模型下都可以得出,同时带肋和气膜孔的下壁面换热最强,光滑的左右壁面换热次之,只带肋的上壁面换热最弱。孔位对下壁面换热影响最大,换热增强因子差别为 7% ,孔位对上壁面换热影响最小,换热增强因子差别为 2.7% 。

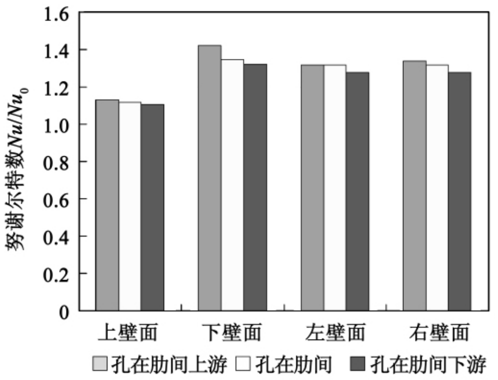


图6　各壁面平均换热增强因子

Fig. 6 Average heat exchange enhancement factors of various wall surfaces

3　结　论

通过数值模拟的方法对气膜孔位于肋间3种位置的通道壁面换热进行了研究，得出如下结论：

（1）孔位对同时带肋和气膜孔的下壁面换热影响最大，为7%；对光滑的左右壁面换热影响较小；对只带肋的上壁面换热几乎没有影响。

（2）带肋和气膜孔的换热通道中下壁面换热最好；左右壁面换热次之，上壁面换热最差。扰流肋对左右光滑壁面换热强化效果好于带肋上壁面换热强化效果。

（3）沿着流动方向，肋扰流和气膜孔出流共同作用导致带肋壁面换热增强因子先增大后减小。光滑壁面的换热增强因子先保持不变后减小。

参考文献：

[1] Han J C. Heat transfer and friction characteristics in rectangular channels with ribturbulators [J]. ASME Journal of Heat Transfer, 1998, 110: 21－328.

[2] JANG Yong-jun, Chen H C, HAN J C. Prediction of flow and heat transfer in rotating two-pass rectangular channels with 45-deg rib turbulators [J]. ASME Journal of Turbomachinery, 2002, 124(4): 124－131.

[3] JANG Yong-jun, Chen H C, HAN J C. Flow and heat transfer in a rotating square channel with 45 deg angled ribs by reynolds stress turbulence model [J]. ASME Journal of Turbomachinery, 2002, 124(4): 146－152.

[4] 裘　云，朱惠人，许都纯，等. 出流孔对内流通道壁面换热影响的实验 [J]. 推进技术，2002，23(6)：477－480.
QIU Yun, ZHU Hui-ren, XU Du-chun, et al. Experiment of the effect of the out-going flow hole on the heat exchange of the wall surface of the internal flow passage [J]. Propulsion Technology, 2002, 23(6): 477－480.

[5] Byerley A R, Jones T V. Ireland P T. Internal cooling passage heat transfer near the entrance to a film cooling hole: entrance to a film cooling hole: experimental and computational Results [R]. ASME Paper 92GT2241. 1992.

[6] 李广超，朱惠人，郭　涛. 带60度肋和气膜孔矩形通道换热研究 [J]. 航空动力学报，2006，21(6)：996－1000.
LI Guang-chao, ZHU Hui-ren, Guo Tao. Study of the heat exchange in rectangular passages with 60-degree -inclined ribs and film holes [J]. Journal of Aerospace Power, 2006, 21(6): 996－1000.

[7] 郭　涛，朱惠人，许都纯. 带90°肋和双排出流孔通道换热特性的实验 [J]. 航空动力学报，2010，25(10)：2249－2254.
GUO Tao, ZHU Hui-ren, XU Du-chun. Experiment of the heat exchange characteristics of the passages with 90-degree-inclined ribs and dual out-going flow holes [J]. Journal of Aerospace Power, 2010, 25(10): 2249－2254.

（丛　敏　编辑）

新技术、新工艺

LM2500将驱动2艘新阿里伯克级驱逐舰

据《Diesel & Gas Turbine Worldwide》2012年7－8月刊报道，GE Marine交付8台LM2500航改型船舶燃气轮机，它们将用来驱动美国海军DDG-51阿里伯克级2艘新驱逐航-DDG113和DDG115驱逐舰。

美国海军接受LM2500通用发动机计划，允许GE控制成本、改进机械加工延长使用寿命。

通用发动机改进将包括LM2500压气机转子、涡轮中间机匣、压气机后机匣和动力涡轮零件。这些改都在燃气轮机范围内，因此不会影响船舶的接口或船上的维护工作。

第一艘DDG-51驱逐舰于1991服役，到2011年年末总计已服役61艘DDG-51阿里伯克级驱逐舰。预计该级舰的使用寿命为35年，但是，美国海军意预延长到40年。

（吉桂明　摘译）

(6). -649 ~654

To explore the mechanism governing the stability enhancement of the self circulation casing treatment, the authors have conducted a detailed study of a low speed centrifugal compressor (LSCC) in which a casing treatment was applied by using a full-three-dimensional numerical simulation. It has been found that the self circulation casing treatment can effectively delay the occurrence of a stall and slightly enhance the efficiency of the compressor and total pressure ratio in zones nearing the stall region. The casing treatment can efficiently lower the blade tip loads, thus decreasing the relative speed of the leakage flow, prohibiting the development of the leakage flow vortices in the clearances of the blade tip passages, reducing the jam of the low speed flow in the passages, enhancing the flow capacity of the passages of the rotor and achieving the aim to enlarge the stable operation range. The comprehensive stability margin can increase by 12.57%. **Key words:** centrifugal impeller, stall margin, self circulation, casing treatment, stability margin

孔-肋相对位置对通道各壁面换热影响 = IInfluence of the Relative Positions of Holes and Ribs on the Heat Exchange Through Various Wall Surfaces in the Passages [刊,汉] / LI Guang - chao, WU Chao-lin, ZHANG Wei, WANG Cheng-jun (Liaoning Provincial Key Laboratory on Advanced Testing Technologies for Aerocraft Propulsion Systems, Shenyang University of Aeronautics and Astronautics, Shenyang, China, Post Code: 110136) // Journal of Engineering for Thermal Energy & Power. -2012, 27(6). -655 ~659

Numerically simulated was the influence of the relative positions of holes and ribs on the heat exchange characteristics of the four wall surfaces of a rectangular passage. As an emphasis, analyzed were the difference of the heat exchange coefficients of the four wall surfaces and influence of the positions of the three types of air film holes on the heat exchange. The calculation results are in relatively good agreement with the test ones. It has been found that the positions of the air film holes have a biggest influence on the lower wall surface concurrently provided with ribs and air film holes. The holes are located at the upstream between ribs will result in the best heat exchange, they are located in the middle of the ribs comes next and they are placed at the downstream between ribs will lead to the worst heat exchange. The positions of the air film holes have a relatively small influence on the heat exchange through the smooth wall surfaces on both left and right and have almost no influence on the upper wall surface provided with only ribs. The turbulent flow around ribs and the suction from the air film holes make the heat exchange coefficient of the lower wall surface have a biggest increase followed by that of the wall surfaces on both left and right and the upper wall surface. Along the flow direction, the joint action of the turbulent flow around the ribs and flow outgoing from the air film holes will force the heat exchange intensification factor of the wall surfaces with ribs to first increase and then decrease while the smooth surface heat exchange intensification factor of the smooth wall surfaces will first keep constant and then decrease. **Key words**: rib, air film hole, internal cooling passage, heat exchange, numerical calculation

CO_2**跨临界热泵循环与朗肯循环耦合系统性能分析 = Analysis of the Performance of a Transcritical** CO_2 **Heat Pump Cycle and Rankine Cycle Coupled System [刊,汉]** /WANG Hong-li, TIAN Jing-rui, LIU Hui-qin, DENG Chuang (College of Metallurgical and Energy Source, Hebei United University, Tangshan, China, Post Code: 063009) //Journal of Engineering for Thermal Energy & Power. -2012, 27(6). -660~663

Proposed was a method for realizing a waste heat recovery from a condenser in a transcritical CO_2 heat pump coupled with a Rankine cycle and thermodynamically analyzed were a Rankine cycle, reheat cycle and a coupled cycle of a transcritical CO_2 heat pump Rankine cycle. The analytic results show that with an increase of the main steam temperature or a decrease of the exhaust gas temperature, the efficiencies of three types of cycles will increase. The average efficiency of the Rankine cycle reaches 31.5%, that of coupled cycle hits 35.5% and that of the reheat cycle is 33.5%. With an increase of the main steam temperature or a decrease of the exhaust gas temperature, the efficiencies of the three types of cycles assume an ascending tendency. Under the same contrast conditions, the efficiency of the coupled cycle is highest while that of the Rankine cycle is lowest and that of the reheat cycle is between them. **Key words**: transcritical CO_2 heat pump, Rankine cycle, reheat cycle, coupled cycle, thermodynamics

对流热采油页岩过程低温余热 ORC **系统热力分析 = Thermodynamic Analysis of a Low Temperature Waste Heat Organic Rankine Cycle System in the Process of the Convection Heat-based Oil Shale Exploitation [刊,汉]** /YANG Xin-le, DAI Wen-zhi (College of Mechanical Engineering, Liaoning University of Engineering Technology, Fuxin, China, Post Code: 123000), ZHAO Yang-sheng, FENG Zeng-chao (Mining Technology Research Institute, Taiyuan University of Science and Technology, Taiyuan, China, Post Code: 030024) //Journal of Engineering for Thermal Energy & Power. -2012, 27(6). -664~669

To recover the low temperature waste heat steam produced during the convection heat-based oil shale exploitation, presented and designed was an organic Rankine cycle system for power generation. Under the condition of specific waste heat steam parameters, based on the working medium R245fa for the cycle, a calculation program was prepared to simulate and analyze the law governing the influence of the off-design condition parameters of the ORC