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Parametric studies on different gas turbine cycles for a high temperature gas-cooled reactor

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Abstract

The high temperature gas-cooled reactor (HTGR) coupled with turbine cycle is considered as one of the leading candidates for future nuclear power plants. In this paper, the various types of HTGR gas turbine cycles are concluded as three typical cycles of direct cycle, closed indirect cycle and open indirect cycle. Furthermore they are theoretically converted to three Brayton cycles of helium, nitrogen and air. Those three types of Brayton cycles are thermodynamically analyzed and optimized. The results show that the variety of gas affects the cycle pressure ratio more significantly than other cycle parameters, however, the optimized cycle efficiencies of the three Brayton cycles are almost the same. In addition, the turbomachines which are required for the three optimized Brayton cycles are aerodynamically analyzed and compared and their fundamental characteristics are obtained. Helium turbocompressor has lower stage pressure ratio and more stage number than those for nitrogen and air machines, while helium and nitrogen turbocompressors have shorter blade length than that for air machine.

1. Introduction

The high temperature gas-cooled reactor (HTGR) is a representative of the next generation of nuclear system. In China, the 10 MW high temperature gas-cooled test reactor (HTR-10) was build in the Institute of Nuclear and new Energy Technology (INET), Tsinghua University, which reached its first criticality in 2000 and begun its full power operation in 2003. The safety related experiments are currently carried out to verify the inherent safety features (Wu et al., 2002). Based on the success of the HTR-10, two projects have been recently launched to further develop the HTGR technology. One is a prototype modular plant denoted by HTR-PM to demonstrate the commercial capability of the HTGR power plant, of which the reactor core power is 380 MW and the power conversion system is steam turbine generator (Zhang et al., 2004). The other is a gas turbine generator system coupled with HTR-10 denoted by HTR-10GT to demonstrate the feasibility of the HTGR gas turbine technology (Wang et al., 2004).

For HTGR technology, the power conversion system currently trends towards utilizing gas turbine generator system worldwide because of its high efficiency and

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Nomenclature

c	absolute velocity (m s^{-1})
c_p	constant-pressure specific heat (J kg^{-1} K^{-1})
c_v	constant-volume specific heat (J kg^{-1} K^{-1})
i	stagnation enthalpy (J kg^{-1})
k	specific heat ratio (c_p/c_v)
p	pressure (Pa)
Δp	pressure drop (Pa) defined in Eq. (2)
q	heat (J kg^{-1})
t	Celsius temperature (°C)
T	absolute temperature (K)
u	blade peripheral velocity (m s^{-1})
v	relative velocity to blade (m s^{-1})
w	work (J kg^{-1})

Greek letters

α	recuperation effectiveness defined in Eq. (6)
φ	isentropic index ($(k-1)/k$)
γ	pressure ratio (p_2/p_1)
η	cycle efficiency defined in Eq. (7)
η_c	isentropic efficiency of compressor
η_t	isentropic efficiency of turbine
$\vec{\eta}_{tc}$	turbocompressor efficiency vector ($[\eta_t, \eta_c]^T$)
$\vec{\theta}$	property modification vector $\left(\left[\frac{c_{p,1-2}}{c_{p,3-4}}, \frac{c_{p,4-5}}{c_{p,3-4}}, \frac{\varphi_{1-2}}{\varphi_r}, \frac{\varphi_{4-5}}{\varphi_r}\right]^T\right)$
τ	temperature ratio (T_4/T_1)
ξ	pressure drop coefficient defined in Eq. (3)
$\vec{\xi}_p$	pressure loss vector $\left(\xi\left[\frac{\xi_{2-4}}{\xi}, \frac{\xi_{5-1}}{\xi}, \frac{\xi_{2a-2b}}{\xi}\right]\right)^T$
Φ	flow coefficient
Ω	load coefficient
Ψ	degree of reaction

Subscript

r	on reference condition
i	node number or blade inlet
j	sub-process number for Eqs. (1), (4), (5) and (13)
in	sub-process inlet
out	sub-process outlet
o	blade outlet

simple structure. For example, the projects of PBMR, GT-MHR, GTHTR300, etc. are designed to utilize gas turbine generator coupled with HTGR (Matzner, 2004; Kostin et al., 2004; Kunitomi et al., 2004). In this paper, the attention is focused on three typical gas turbine cycles for the HTGR. These cycles are thermodynamically analyzed and their main components, turbomachines, are aerodynamically studied to show the fundamental features of the cycles and required turbomachines.

2. HTGR gas turbine cycles

2.1. Three typical gas turbine cycles

The high temperature gas-cooled reactor and the gas turbine generator can be practically coupled in various schemes which can be concluded as three typical HTGR gas turbine cycles in this paper, that is, direct cycle, closed indirect cycle and open indirect cycle as shown in Figs. 1–3.

Fig. 1 depicts the schematic diagram of HTGR gas turbine direct cycle. High temperature and high pressure helium from the reactor core flows into the turbine directly to rotate the turbine by gas expansion. The turbine drives the generator and compressors

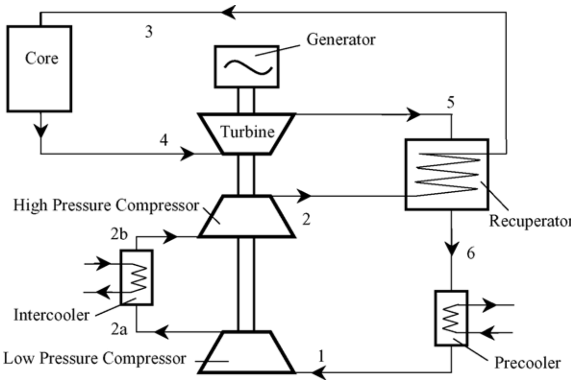

Fig. 1. Direct cycle (helium).