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Analysis of a novel solar energy-powered Rankine cycle for combined power and heat generation using supercritical carbon dioxide

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Abstract

Theoretical analysis of a solar energy-powered Rankine thermodynamic cycle utilizing an innovative new concept, which uses supercritical carbon dioxide as a working fluid, is presented. In this system, a truly 'natural' working fluid, carbon dioxide, is utilized to generate firstly electricity power and secondly high-grade heat power and low-grade heat power. The uniqueness of the system is in the way in which both solar energy and carbon dioxide, available in abundant quantities in all parts of the world, are simultaneously used to build up a thermodynamic cycle and has the potential to reduce energy shortage and greatly reduce carbon dioxide emissions and global warming, offering environmental and personal safety simultaneously. The system consists of an evacuated solar collector system, a power-generating turbine, a high-grade heat recovery system, a low-grade heat recovery system and a feed pump. The performances of this CO_2-based Rankine cycle were theoretically investigated and the effects of various design conditions, namely, solar radiation, solar collector area and CO_2 flow rate, were studied. Numerical simulations show that the proposed system may have electricity power efficiency and heat power efficiency as high as 11.4% and 36.2%, respectively. It is also found that the cycle performances strongly depend on climate conditions. Also the electricity power and heat power outputs increase with the collector area and CO_2 flow rate. The estimated COP_{power} and COP_{heat} increase with the CO_2 flow rate, but decrease with the collector area. The CO_2-based cycle can be optimized

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Nomenclature

A_s	Efficient area of evacuated solar collector (m^2)
C_p	Specific heat (J/kg °C)
$f1$, $f2$, $f3$	Functions used in PROPATH 12.1 for calculating the thermodynamic parameters of carbon dioxide
h	Convective heat transfer coefficient ($W/m^2 K$)
h	Specific enthalpy (J/kg)
L	Length of metal tubes in evacuated solar collector (m)
m_c	Mass flow rate of carbon dioxide (kg/s)
n	Number of metal tubes in evacuated solar collector (dimensionless)
P	Pressure (MPa)
q_i	Incident solar flux (W/m^2)
Q_T	Electric power output from the turbine (W)
Q_{H1}	Heat power output from the high-temperature heat recovery system (W)
Q_{H2}	Heat power output from the low-temperature heat recovery system (W)
r	Radius (m)
s	Specific entropy (J/kg K)
T	Temperature (°C)

Greek letters

α	Solar absorbtance (dimensionless)
σ	Stefan–Boltzmann constant ($W/m^2 K^4$)
ε	Thermal emittance (dimensionless)
τ	Solar transmittance (dimensionless)
λ	Thermal conductivity (W/m K)
δ	Thickness of the inner glass tubes (m)
η	Turbine efficiency; a value of 0.9 is used in the present study

Subscripts

a	Ambient
b	Inner glass tube
c	Selective coating
d	Metal tube
e	Carbon dioxide
f	Absorber coating
g	Glass
o	Glass envelope
1	Outlet of solar collector
2	Outlet of turbine
3	Outlet of the CO_2-loop in the high-temperature heat recovery system
4	Outlet of the CO_2-loop in the low-temperature heat recovery system
5	Outlet of feed pump