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Thermodynamic analysis of a low-temperature waste heat recovery system based on the concept of solar chimney

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ABSTRACT

The utilization of low-temperature waste heat draws more and more attention due to serious energy crisis nowadays. This paper proposes a low-temperature waste heat recovery system based on the concept of solar chimney. In the system, low-temperature waste heat is used to heat air to produce an air updraft in the chimney tower. The air updraft propels a turbine fixed at the base of the chimney tower to convert waste heat into electricity. The mathematical model of the system is established based on first law and second law of thermodynamics. Hot water is selected as the representative of low-temperature waste heat sources for researching. The heat source temperature, ambient air temperature and area of heat transfer are examined to evaluate their effects on the system performance such as velocity of updraft, mass flow rate of air, power output, conversion efficiency, and exergy efficiency. The velocity of air demonstrates a better stability than the mass flow rate of air and the pressure difference when temperature of heat source, ambient air temperature or area of heat transfer changes.

1. Introduction

With the rapid consumption of fossil energy and changes of global climate, improving the energy utilization efficiency has drawn more attention. One of the methods to increase the energy utilization efficiency is to recover low-temperature (between ambient temperature and 523 K [1]) waste heat which widely exists in modern industry. For example, low-temperature waste heat could be recovered to generate electricity by thermodynamic cycles such as organic Rankine cycle (ORC), and supercritical Rankine cycles (SRCs) [2–5]. In addition, other ways are also examined to use low-temperature waste heat, such as the chemical heat pumps, and thermal energy storage technologies [1]. All in all, recovering low-temperature waste heat effectively has been the focus of a great deal of researches nowadays.

The ways mentioned above to utilize low-temperature heat sources have improved the energy utilization efficiency much. However, they still have some disadvantages. For example, ORC requires a high performance seal system and most of organic working fluids are proved to be harmful to the atmosphere. What is more, organic working fluids are usually very expensive. Therefore, an innovative way to recover low-temperature waste heat based on the natural substance and that has little negative effects on environment should be explored. Due to some similarities to solar energy, low temperature waste heat could be recovered based on the concept of solar chimney tower. Low-temperature waste heat could be used to heat air and the heated air flows through an upright or slant channel to produce an air flow of stable velocity to drive turbine, yielding power output. The method is based on the effect of solar chimney tower.

The solar chimney, as illustrated in Fig. 1, operates like a hydroelectric power plant, but it uses hot air instead of water to propel a turbine [6]. It consists of a transparent roof collector, a central chimney tower and one or more turbo generators at the base. As air is heated by solar radiation, air pressure difference comes into being. Much air is drawn into the central chimney tower to form hot air updraft. The air updraft is used to drive a turbine fixed at the base of the central chimney tower to generate electricity. In recent years, many researches have been done on solar chimney tower. Schlaich et al. [7] did much work on the design of commercial solar chimney tower and he gave an overview on solar chimney tower theory, practical experience with prototypes, and economies of large scale solar chimney tower power plants. Bilgen and Rheault [8] studied solar chimney power plants with slant collector for high latitudes and he found that the overall thermal performance of the solar chimney power plants at high latitudes was about 0.48%, which was slightly better than that with horizontal collector fields at low latitudes with favorable climate. Harte and Van Zijl [6] studied structural stability of solar chimney towers exposed to dynamic wind action and he concluded that the material non-linearities, like cracking and crushing of concrete, would heavily influence the dynamic behaviors and the long-term durability. Papageorgiou [9] compared the construction cost of solar chimneys

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Nomenclature

A	area, m^2
A_o	area of outside tubes, m^2
A_i	area of inside tubes, m^2
A_t	area of fins, m^2
c	velocity, $m\ s^{-1}$
c_p	specific heat at constant pressure, $kJ\ kg^{-1}\ K^{-1}$
d	diameter, m
$E_{x,H}$	exergy, $kJ\ s^{-1}$
e	enthalpy, $kJ\ kg^{-1}$
g	acceleration of gravity, $m\ s^{-2}$
H	height of chimney tower, m
H_0	lift of pump, m
h	convective heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
k	overall heat transfer coefficient, $W\ m^{-2}\ K^{-1}$
$\dot{m}$	mass flux, $kg\ s^{-1}$
N	number of tubes
P	power output, kW
Pr	Prandtl number
p	pressure, Pa
Q	heat, $kJ\ s^{-1}$
q_v	volume flow rate, $m^3\ s^{-1}$
Re	Reynolds number
r	thermal resistance, $m^2\ K\ W^{-1}$
r_j	fin gap thermal resistance, $m^2\ K\ W^{-1}$
s	entropy, $J\ kg^{-1}\ K^{-1}$
T	temperature, K
t	temperature, °C
x	pressure distribution coefficient
z	height, m

Greek letters

λ	thermal conductivity, $W\ m^{-1}\ K^{-1}$
μ	kinematic viscosity coefficient, Pa s
v	specific volume, $m^3\ kg^{-1}$
ρ	density, $kg\ m^{-3}$
η	efficiency, %

Subscripts

1	inflow
2	outflow
a	air
ave	average
chi	chimney
con	conversion
d	dynamic
exe	exergy
f	flow
hy	hydraulic
i	in
m	machine
max	maximum
min	minimum
net	net
o	out
pump	pump
real	real
s	static
loss	loss
tot	total
u	useful work
v	volume
w	water
wall	wall

with two different kinds of solar chimney constructions, reinforced concrete structures (Concrete Solar Chimneys, CFCs) and inflated structures (Floating Solar Chimneys, FSCs) and he concluded that FSC Technology Power Plants was five to six times cheaper than CFC Technology Power Plants. Fluri and Von Backström [10] examined the performance of the power conversion unit (PCU) of a solar chimney power plant and confirmed the assumption made by many other researchers that the total-to-total efficiency of the PCU was 80%. Cao et al. [11] found that the solar chimney power plant showed better performances in spring and autumn than in summer and winter when he studied a sloped solar chimney power plant in Lanzhou of China. What is more, Zandian and Ashjaee [12] combined a cooling tower and a solar chimney to improve thermal efficiency of a steam Rankine cycle and a hybrid system model with height of 200 m and diameter from 10 m to 50 m was studied with CFD simulations. They found that a maximum increase of 0.37% in the thermal efficiency of a 250 MW fossil fuel power plant unit could be obtained.

Being similar to solar chimney power plant, low-temperature waste heat could be used to generate power output based on the fundamental theory of solar chimney tower. Then, this study proposes a low-temperature waste heat recovery system based on the concept of solar chimney tower. Low-temperature waste heat serves as the heat sources instead of solar radiation. Hot water is selected as the representative of low-temperature waste heat resources for researching. The mathematical model of the system is established based on the first and the second law of thermodynamics. The heat source temperature, ambient air temperature and area of heat transfer are examined to evaluate their effects on the system performance such as velocity of air, mass flow rate of air, power output, conversion efficiency, and exergy efficiency.

2. System description and mathematical model

2.1. System description

Fig. 2 illustrates the schematic diagram of low-temperature waste heat recovery system based on the concept of solar chimney tower. In this system, industrial hot water is selected as the low-temperature heat source. The system consists of a heat exchanger, a chimney tower, a turbine and a pump. The chimney tower is just like a chimney with large height and diameter. The heat exchanger is located at the base of the chimney tower. A turbine is fixed above the heat exchanger at the entrance of the chimney tower. The pump enables hot water to go through the heat exchanger to heat the ambient cold air. As hot air is lighter than cold air, pressure difference is produced between hot air inside and ambient cold air outside at the base of the chimney tower. Hot air is accelerated by the pressure difference and rises up along the tower. Then, suction from the tower draws in more air from the bottom of the tower, and cold air enters the chimney tower from the base of the tower. Thus, hot water causes a continuous updraft in the tower. The kinetic energy of the updraft is converted into useful work by the turbine fixed in the chimney tower [13]. As long as the pump is continuously in operation, the electricity could be generated steadily for 24 h a day. A part of the electricity generated by turbine is consumed by the pump and the left can be transmitted to the power grid.