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Integration of a free-piston Stirling engine and a moving grate incinerator

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Abstract

The feasibility of recovering the waste heat from a small-scale incinerator (designed by Industrial Technology Research Institute) and generating electric power by a linear free-piston Stirling engine is investigated in this study. A heat-transfer model is used to simulate the integration system of the Stirling engine and the incinerator. In this model, the external irreversibility is modeled by the finite temperature difference and by the actual heat transfer area, while the internal irreversibility is considered by an internal heat leakage. At a fixed source temperature and a fixed sink temperature, the optimal engine performance can be obtained by the method of Lagrange multipliers.

From the energy and mass balances for the interesting incinerator with the feeding rate at 16 t/d, there is enough otherwise wasted energy for powering the Stirling engine and generate more than 50 kW of electricity.

Keywords: Incinerator; Free-piston Stirling engine; Waste heat recovery

1. Introduction

Incineration with heat recovery is an attractive process of recovering energy in some countries [1,2]. The conversion of waste heat to power is very desirable to the areas without sufficient energy resources. It has been a common practice to convert water into superheated steam by absorbing the otherwise wasted energy, the obtained steam can then be used to power a steam turbine and generate electricity (called steam turbine GENSET). For instance, in Japan 769 MW of electric power was generated by 181 large-scale incineration plants in 1998 [3]. However, it is not appropriate to use steam turbine GENSET to recover energy from a small-scale incinerator (say less than 500 t/d). This is because the thermal efficiency of steam turbine will drastically drop as the turbine capacity decreases [4,5]. On the other hand, Stirling engine can retain high efficiency over power range from a few tens of watts to several kilowatts and is very suitable to use as Stirling GENSET for a small or medium scale incinerator.

Among several types of Stirling machines, the free-piston Stirling engine matched with a linear alternator (called free-piston Stirling GENSET) has the most mechanical simplicity and the least friction loss due to mechanical movement [6]. Some technical difficulties inherent to linear alternator such as the piston's overstroking and under-damped problems have been gradually resolved [7]. With many great features in power generation, the free-piston Stirling GENSET has been considered in this study as the potential candidate to recover the waste energy from a small-scale incinerator, designed by the Industrial Technology and Research Institute (ITRI) of Taiwan.

Since the Stirling engine is an external combustion engine, which means the energy used to power the engine movement is entirely obtained from the external source, the losses due to the heat transfer in and out of engine or due to the heat bypass within the engine structure may be more important than that of mechanical losses. Recently, Kongtragool and Wongwises [8,9] performed the studies and found the power and efficiency of a Strling engine were strongly affected by the irreversible heat transfer process

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Nomenclature

$A_{in,H}$ the inner area of engine's hot-end surface (m^2)
$A_{out,C}$ the outer area of engine's cold-end surface (m^2)
$A_{out,H}$ the outer area of engine's hot-end surface (m^2)
$F_{H,O}$ the view factor from hot-end surface to source surface
$h_{coolant}$ the convective coefficient of cooling water (W/m^2/K)
h_{He} the convective coefficient of helium gas (W/m^2/K)
$(HA)_C$ the thermal conductance from the inner fluid to the outer cold-end surface (W/K)
$(HA)_{fgas}$ the thermal conductance between hot-end surface and flame gases (W/K)
$(HA)_H$ the thermal conductance from the outer hot-end surface to the inner fluid (W/K)
$(HA)_{sink}$ the thermal conductance from the outer cold-end surface to the heat sink (W/K)
$\dot{Q}_C$ the heat transfer from working fluid to engine's cold-end surface (W)
$\dot{Q}_{conv}$ convection heat transfer from heat source to hot-end of engine (W)
$\dot{Q}_H$ heat transfer from hot-end surface to working fluid (W)
$\dot{Q}_{rad}$ radiation heat transfer from heat source to hot-end of engine (W)
$\dot{Q}_{sink}$ the rejected heat transfer from working fluid (W)
$\dot{Q}_{source}$ heat transfer from the heat source (W)
$\dot{Q}_T$ thermal leakage and other internal irreversibilities (W)
T_C the surface temperature of engine's cold-end (K)
T_{fgas} the temperature of flame gases (K)
T_H the surface temperature of engine's hot-end (K)
T_L lowest fluid temperature (K)
T_{sink} the temperature of heat sink (K)
T_{source} the temperature of heat source (K)
T_U highest fluid temperature (K)
$\dot{W}$ cycle-average power (W)
α absorptivity of the surface exposed to flame
δ $(HA)_{sink}/(HA)_C$
ε $(HA)_C/(HA)_H$
η_{Carnot} the thermal efficiency of Carnot cycle
η_{endo} the thermal efficiency of internal reversible cycle
η thermal efficiency
θ $(HA)_{sink}/(HA)_H$
λ_m eigen-values of Lagrange Multiplier equations
ξ the ratio of heat which actually flow into the fluid
σ Stefan–Boltzmann constant, 5.67×10^{-8} W/m^2K^4
τ $\alpha A_{H,O}F_{H,O}\sigma/(HA)_H$
ϕ_m constraint function m

[8], and also affected by regenerator effectiveness and dead volume [9].

In this study, a heat transfer model is used to simulate a realistic Stirling engine, the effects due to engine's irreversibilities on the output power and thermal efficiency will be modeled by mathematical formulation, and Lagrange multipliers method is employed to optimize the net-work output under the fixed source and sink temperatures.

2. Incinerator and waste heat

The designed incinerator is of a modular type composed of a feeding gear, a dual combustor with primary and secondary combustion chambers, a heat recovery system, and an air pollution control system. The burning capacity ranges 16–50 t/d.

In order to comply to the regulation set by the Environmental Protection Administration of Taiwan to eliminate toxic gases, the temperature of secondary chamber has to be kept above 1273 K. Therefore, the Stirling GENSET is intended to be installed on the boundary of secondary combustor with the hot-end surface embedded inside the chamber, see Fig. 1. The control of chamber's temperature is automatically made by adjusting an auxiliary fuel pump, the flow rate of preheated air from the heat recovery system, and the air flow rate directly from outside ambient.

The available waste heat at the feeding of 16 t/d was estimated to be 314 kW from the energy balance for both combustors [10]. The estimation was performed under the conditions of burning the sample waste with 100% excess air. A complete combustion was assumed, lower heating values were used in the calculation, and no auxiliary fuel was burnt. The content data for sample waste was provided by ITRI, in which they have analyzed the buck wastes collecting from four different industrial parks.

3. Heat transfer model

To recover the waste heat, the hot-end surface of Stirling engine is embedded inside the combustion chamber, see Fig. 1. The temperature of heat source T_{source}, shown in Fig. 2, represents the controlled chamber temperature of incinerator. The temperature of heat sink T_{sink} in Fig. 2 stands for the temperature of coolant used to cool down the cold-end surface, see Fig. 1. T_H is the surface temperature of engine's hot end (receiving flame heat), and T_C the surface temperature of engine's cold end (contacting with coolant). Since the power cycle (thermodynamic cycle) is