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Research paper

Heat transfer enhancement in tubular heater of Stirling engine for waste heat recovery from flue gas using steel wool

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HIGHLIGHTS

- An approach was given to improve the performance of heater of Stirling engine.
- Steel wool can enhance the heat transfer of high temperature flue gas.
- The combined heat transfer coefficient increases at a successively slower rate.
- An optimal porosity of steel wool exists for the heat transfer enhancement.

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ABSTRACT

Experimental tests were performed on a pilot Stirling engine used for waste heat recovery from flue gas to assess approaches to effectively enhance heat transfer within its tubular heater. For these tests, the heat transfer coefficient of flue gas was measured for the original heater and then after it had been filled with heat-resistant steel wool. The experimental results show that the steel wool effectively enhanced the combined heat transfer coefficient on the outer surface of heater tubes; as the porosity of the steel wool was decreased, the combined heat transfer coefficient continued to increase but at a successively slower rate. These results provide an approach for heat transfer enhancement from high temperature flue gas for tubular heat exchangers, and contribute to design optimization of a tubular heater in a Stirling engine.

1. Introduction

Some exhaust gases from industrial equipment have high temperatures: examples include the exhaust gas from billet heating furnaces, which is in the range of 900 °C to 1200 °C; the exhaust gas from dry process cement kilns, which is in the range of 600 °C to 800 °C; the exhaust gas from glass melting furnaces, which is in the range of 650 °C–900 °C; and, the exhaust gas of auto vehicles, which is in the range of 750 °C–800 °C [1–3]. Therefore, a significant amount of high quality heat is available in the exhausts of these processes and, if recovered, would offer benefits related to conserving energy, reducing the consumption of fossil fuels and offering decreased operational costs.

In recent years, Stirling engine technologies have matured to the point of having practical application potential for power capacities from a few kilowatts to dozens of kilowatts. Importantly, Stirling engines, an external combustion engine, are noted for their high efficiencies compared to steam engines, quiet operation, and ability to use almost any heat source. The heat energy source is generated external to the Stirling engine rather than by internal combustion as with the Otto cycle or Diesel cycle engines. Due to its unique features, the Stirling Engine is a powerful candidate to recover the waste heat of the exhaust flue gases by converting it into power.

As a consequence of closed cycle operation, the heat energy driving a Stirling engine must be transferred from a heat source to the working medium by heat exchangers and finally to a heat sink. For small, low-power Stirling engines, the heater or hot-side heat exchanger may consist simply of the walls of a hot vessel, but for larger power requirements the heat exchanger has to have a greater heating surface area than the walls of the hot vessel. Hence, typical

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implementations of heat exchangers are internal and external fins or multiple small-bore tubes; these designs are classified as either finned tubular or plain tubular types according to the type of heating surface layout. For the latter, the heater is composed of multiple small-bore tubes in which the working medium, such as air, hydrogen or helium, usually is at high pressure and velocity so that the heat transfer coefficient within the tube is relatively higher than that of exhaust gas on the outer side of the tubes. The dominant heat resistance of the heat transfer process in the heater of Stirling engine is on the outer side of the tubes, i.e. the flue gas side. To reduce this heat transfer resistance and to increase the heat transfer between the flue gas and working medium, this research was conducted with the addition of a heat-resistant steel wool that was placed into the space between the outside of the tubes. Besides increasing the heat transfer area, the steel wool should have a higher emissivity than the flue gas at the high temperatures, which can enhance the transfer of heat from the flue gas to the outer tube surfaces of tubes. Furthermore, because the steel wool has a higher specific heat than the flue gas and has the ability to accumulate heat energy, its presence was thought to offer more stability in heat transfer and, thereby, promote smoother engine operation as the flue gas flow rates and temperatures fluctuated.

There existed some researches on heat transfer enhancement of low temperature gas flow in tube by filling porous media including metal foam and metal wool [4–16], but no one focused on heat transfer enhancement of flue gas outside the tube, and especially, at high temperature.

Hence, this research evaluates heat transfer coefficients while using high temperature flue gas with steel wool added into a tubular heater of a Stirling engine. It is significant on waste heat recovery of flue gas and optimal design of the heater of Stirling engine.

2. Experimental set-up and procedure

The experimental system is shown in Fig. 1. It is composed of a gas mixing system,I, water cooling system,II, Stirling engine power system, III, burner and temperature acquisition system, IV, and the Stirling engine control system,V.

During tests, the air was compressed using the air compressor, 1, which then flowed through flow meter, 2, heat regenerator, 3, and into the gas mixing tank, 4. High pressure methane flowed from the methane cylinder, 5, through flow meter, 6, and entered the gas mixing tank, 4, where the air and methane were mixed proportionally to give known gas mixture concentrations. After the mixer, the gas flowed through a flame arrester, 7, and into a porous medium burner, 8, in which the gas was burned. Gas combustion produced the flue gas for experimental use.

By adjusting the proportion of air and methane as well as their flow rates, the flue gas temperatures and flow rates were changed to meet the requirements of the experiments. The flue gases were flowed into the heater of the Stirling engine, 9, in which heat is released to the working medium of Stirling engine operation. The exhaust gas from the heater flowed into a regenerator which preheated the air from the air compressor, 1, for heat recovery. The Stirling engine was cooled using water which is circulated by a water pump. Fig. 2 shows the photo of the experimental system.

The Stirling engine is shown in Fig. 3; it is a small pilot β type Stirling engine with power capacity of 500 W, made in Beijing, China. Its 28 heat exchanger tubes were U-shaped with diameters of 6 mm, and were annularly welded onto a base of the heater, as shown in Fig. 4. The schematic diagram of the heater is displayed in Fig. 5; it was made of seamless steel pipe and had an inner diameter of 160 mm, height of 180 mm and wall thickness of 8 mm. During operation, flue gas entered into the heater from its top inlet, moved downwards, and via the circular flue gas return chamber at the bottom of the heater exited from the outlet at its bottom side. From Fig. 5, it also can be seen that the gas flow in the heater was not purely longitudinal flow or cross flow, but inclined flow to enable washout of the tubes of heater. The heater shell had an outer insulation of ceramic wool. The porous medium burner, which can burn methane and air mixtures with a wide range of concentrations and flow rates, enabled the production of flue gas with a wide variety of flow rates and temperatures to satisfy a broad range of experimental conditions.

Steel wool, also known as wire wool or wire sponge, consists of bundles of fine steel filaments, as shown in Fig. 6. It is commonly used as an abrasive in finishing and repair work for polishing wood or metal objects, cleaning household cookware, cleaning windows and sanding surfaces. At present, steel wool products are supplied in grades from the extra coarse (100 μm filament) to the super fine (25 μm filament). Because the flue gas from the burner had a temperature higher than 700 °C, a steel wool with 1Cr13 composition and a coarse grade (90 μm filament) was used; this steel wool was heat resistant and could withstand temperatures up to 900 °C. The steel wool was placed into the heater and covered the heat exchanger tubes. By varying the amount of steel wool placed into the heater, different porosities of steel wool ranging from 0.9857 to 0.9473were obtained.

The temperature acquisition system comprised of eight thermocouples (Type K) and one readout. The thermocouples accuracies were grade 1 over a temperature range of 1–1000 °C. Two

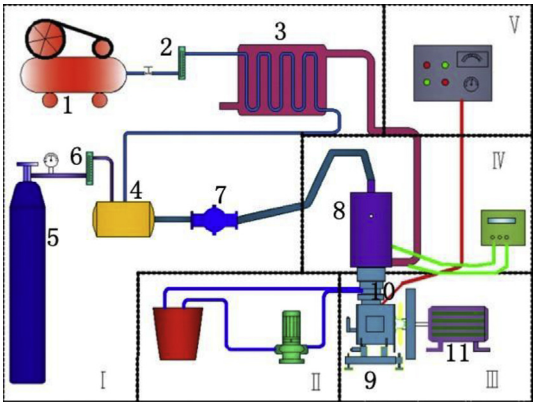

Fig. 1. Schematic diagram of experimental system.

Fig. 2. Photo of experimental system.