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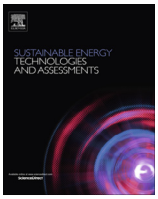

Original Research Article

Experimental investigation of energy and exergy efficiency of a pulsating heat pipe for chimney heat recovery

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ABSTRACT

A prototype heat exchanger is proposed for exhaust heat recovery by means of pulsating heat pipe. The device is made up of an exhaust channel, an air channel, and a row of pulsating heat pipes with the filling ratio of 40% and ethanol and silver nano-fluid as working fluids. The exhaust hot gas from the combustion of natural gas feeds the device. For exergy analysis of the device, the inlet and outlet temperatures of the hot gas and cold air were measured with appropriate devices. Having the exergy of each flow, the exergetic efficiency of the system was calculated at different inlet temperatures. The calculations were carried out for two distinct working fluids within the heat pipes. The energy analysis results show that ethanol, at an inlet smoke temperature of 120 °C, has the best functionality. Exergy analysis also demonstrated the better performance of silver nano-fluid compared to ethanol. The use of silver nano-fluid instead of ethanol increases exergy efficiency as much as 1–3% and decreases exergy losses as much as 8–14%.

Introduction

Over the past few centuries, the world economy has been dependent on non-renewable fossil fuels. Until the oil crisis of 1973, the necessity of long term rethinking and plans to address energy optimization was not felt. After the crisis, attention was focused on ways to reduce fossil energy consumption and to replace it with the new renewable energies. Of course, there are some other reasons as well, such as climate changes, global warming due to the greenhouse effect, energy security, rising fuel prices, and strict environmental regulations for gas emissions that drove a comprehensive research on clean technologies.

One of the main ways to reduce fuel consumption is to recycle the exhaust heat from the combustion of fossil fuels. This reduces carbon dioxide emissions as well as fuel consumption, which would positively affect environmental preservation [1–12].

Heat pipes are one of the best options for heat transfer in most cases and are considered to be effective for heat loss recovery. The advantage of using heat pipe over other conventional methods is that this system can transfer huge amounts of heat through a small cross section and along a considerable distance without receiving any power. In addition, simple manufacturing and design, low temperature drop along the heat pipe, application in a wide range of temperatures (4–2000°K), and the ability to control and transfer high heat flow rates at different temperatures are considered as other advantages [13,14].

The new generation of heat pipes, called pulsating heat pipes, were invented by Akachi in 1990s [15,16]. Due to the use of a combination of sensible and latent heat transfer, the pulsating heat pipes are more efficient than conventional heat pipes. Simple design and low price are also among other superiorities of the pulsating heat pipe in comparison with other heat transfer equipment.

Alawi et al. [17] presented an overview of different research works and recent developments in the field of heat transfer enhancement using nanofluids in various types of heat pipes. Their review showed that adding nanoparticles to the working fluids can increase the heat transfer and reduce the heat resistance of the heat pipes.

Lin et al. [18] experimentally investigated the thermal performance of pulsating heat pipes using nano-fluids. They used water-based silver nano-fluid in various volume percents (100 ppm, 450 ppm), as well as different filling ratios (20%, 40%, 60%, 80%). Silver nano-particles were 20 nm in diameter.

The results showed that using nano-fluid instead of water improves the thermal efficiency of pulsating heat pipes. The best filling ratio was reported to be 60% and the best volumetric concentration 100 ppm. These results were obtained with the input power of 85 W. Furthermore, the mean temperature difference between the evaporator inner wall and saturated vapor was

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Nomenclature

A	Area [m^2]
c_p	Specific heat [kJ/kg K]
D	Diameter [m]
Ex	Exergy ratio [W]
g	Gravity [m/s^2]
h	Specific enthalpy [kJ/kg]
m	Mass [kg]
Q	Heat transfer [kJ]
s	Specific entropy [kJ/kg K]
T	Temperature [k]
V	Velocity [m/s]
W	Work [kJ]
x	Mole percent [%]
ψ	Specific exergy [kJ/kg]
ε_p	Exergy transfer efficiency
ρ	Density [kg/m^3]
η	efficiency

Subscripts

h	Hot flow
c	Cold flow
i	Inlet
o	Outlet
$\circ$	Ambient condition

reduced to 7.8 K. This reduction is equivalent to a 15% reduction in the final heat pipe thermal resistance.

The heat transfer of a closed two-phase thermosiphon using pure water and different nanofluids was compared by Khandekar et al. [19] and Noie et al. [20].

Wang et al. [6] carried out a comprehensive review on different techniques for exhaust heat recovery from internal combustion engines. They came to the conclusion that the most widely used method for this task is using the Rankin cycle. Moreover, they reported up to 30% energy consumption saving in an internal combustion engine.

Srinivasan et al. [7] investigated exhaust heat recovery in a dual fuel low-temperature combustion engine by means of anorganic Rankin cycle. They showed that the amount of carbon dioxide produced can be reduced up to 18% in this method.

A new combined cycle to recycle the heat in the internal combustion engines was introduced by He et al. [8]. The new cycle was a combination of a Kalina cycle for low-temperature recovery and an organic Rankin cycle for high-temperature recovery.

By examining a variety of cycles for direct and indirect heat recovery, Liu et al. [10] concluded that the indirect method is the better one.

Messerer et al. [21] investigated thermal recovery in combustion engines, in which fossil fuels were replaced by wood, and reported the recovered heat rate.

An increment in thermal efficiency (2.9–3.7%) was reported for heat recovery by Rankin cycle in hydrogen internal combustion engines by Yamada et al. [22].

Srimuag and Amatachaya [23] discussed the applications of heat pipes in thermal recovery and factors affecting the conventional, pulsating, and closed thermo syphon types. They believed that one of the best ways to save energy is using heat pipe heat exchangers.

Shabgard et al. [24] demonstrated the effect of using heat pipes on latent heat storage in solar systems through exergy analysis. By means of exergetic analysis in air conditioning systems, Fang et al. [25] illustrated that the use of heat pipes in ice storage systems enhances exergy efficiency as much as 9.55% compared to “ice-on-coil” ice storage systems.

Naphon [26] carried out several exergy studies on horizontal micro-fin tube heat exchangers.

The effect of exergy transfer in heat exchangers on finite pressure drop was studied by Wu et al. [27]. They presented a relation for exergy transfer efficiency, both in isobar and finite pressure drop cases.

As stated above, the most papers in the literature considered the heat transfer enhancement, advantages and disadvantages of using nanofluids in different types of heat pipes. The past research seldom addressed the exergy components of heat pipes and the probable differences were studied using energy-based analyses. Moreover, to determine the characteristics of the working fluid, exergy analysis has not been considered in previous studies.

The performance of a pulsating heat pipe for heat recovery is investigated experimentally from both energy and exergy points of view. Finally, according to the experimental results, the exergetic efficiency and exergy transfer efficiency are compared for two different working fluids, namely ethanol and silver nano-fluid.

Experimental setup

Pulsating heat pipes

There are two types of pulsating heat pipes, namely closed-loop and open-loop as illustrated in Fig. 1. The closed-loop type is more efficient, since it provides the possibility of fluid flow in the pipes.

When the heat pipe is partially filled with a proper working fluid, the fluid will be distributed in pipes as slug-plug due to the adhesion effect in small diameter pipes (according to Fig. 1). The heat flux at the start of the process is not sufficient for the movement of the working fluid. With a further increase in heat flux, the working fluid in the heat pipe starts moving and heat transfer is greatly improved [28]. A unique feature of the pulsating heat pipe is that the evaporated fluid in the evaporation section flows toward the condenser under its own increasing pressure force and moves the fluid in the condenser toward the evaporator in the adjacent pipe. This phenomenon, as will be explained later on, will make the performance of pulsating heat pipe less dependent on gravity.

Pulsating heat pipe fabrication

Pulsating heat pipes made for this study consist of two rows of closed-loop pulsating heat pipes with an internal diameter of 2 mm and an external diameter of 4 mm. Each row consists of 18 turns of pipes, in a way that the total height of 56 cm was considered for the pulsating heat pipe. There was a 27-cm evaporator, 27-cm condenser, and 2 cm for the adiabatic section, which is negligible. To achieve maximum heat transfer, copper pipes were selected. Then, in order to create an pulsating heat pipe, copper pipes were bent to a U-shaped pipe by a pipe bender. In this case, 18 turns were made in a distance of 100 cm.

First, the air was evacuated from the pipe. To ensure complete evacuation of air in a closed-loop pulsating heat pipe, the air inside the closed-loop pulsating heat pipe was evacuated for approximately 30 min using a vacuum pump to get to the set pressure of less than 15 Pa. This relatively long time duration was set