Iranian Journal of Science & Technology, Transaction B, Vol. 28, No. B6
Printed in The Islamic Republic of Iran, 2004

"Research Note"

ENERGY CONSERVATION BY WASTE HEAT RECOVERY IN INDUSTRY USING THERMOSYPHON HEAT EXCHANGERS*

S. H. NOIE,** M. LOTFI AND N. SAGHATOLESLAMI

Dept. of Chemical Eng. Faculty of Eng., Ferdowsi University of Mashhad, Mashhad,
P.O. Box: 9177948944-1111, I. R. of Iran
Email: noie@um.ac.ir

Abstract– Conservation of energy by waste heat recovery is important not only for cost reasons, but also for reducing primary energy consumption as well as reducing carbon dioxide production. This paper explains and discusses the simulation, performance, and successful applications of thermosyphon heat exchangers (THE's) for recovering waste heat from exhaust gases in industrial plants. The advantages of this system are compactness, flexibility of system size, ease of operation, and minimum maintenance requirements. The thermosyphon heat exchanger can satisfactorily act as a pre-heater of air in boilers and furnaces using the heat recovered from the exhaust. In this work, one successful industrial practice is explained using thermosyphon heat exchanger. The THE was simulated to recover waste heat from the exhaust of a nearly 7 ton boiler in the SAMEN company. The energy recovered from the flue gas is used to preheat the incoming air to the boiler. The average rate of waste heat recovery and thermal effectiveness obtained from computer simulation are 100 kW and 40%, respectively. The payback period was less than two years. The evaluation of the thermal performance of the THE was based on the effectiveness-NTU and LMTD methods to obtain the heat transfer characteristics.

Keywords– Energy conservation, heat pipe, thermosyphon heat exchanger

1. INTRODUCTION

Since the first energy crisis in 1973, industries have started putting more and more attention and effort into energy conservation. Increasing fuel costs and energy conservation are two of the most important considerations to be taken in new heat exchangers such as heat pipe (thermosyphon) heat exchangers. A two-phase closed thermosyphon which is actually a wickless, gravity-assisted heat pipe with a small amount of working fluid, which is in equilibrium with its own vapor sealed inside container (pipe wall and end caps), is a very effective heat transfer device, which allows a very high rate of heat transfer in the process of evaporation and condensation. In addition, the two-phase closed thermosyphon is simple, cheap, and easy to construct using small end-to-end temperature drops. It has an extremely wide temperature application range (4-3000K), and is an effective device that requires no external driving force other than the temperature differences [1-3].

Heat pipe (thermosyphon) heat exchangers have been used in many ways, in boilers, furnaces and dryers, especially for energy recovery in industry [4-11]. Some papers reported on their thermal performance in severe conditions [12-13]. There have been quite a few computer simulation studies of THE's, however, more research on simulation and performance are still needed.

This paper presents an achievement report on one case study in industrial practices. In this work, a thermosyphon heat exchanger was simulated to recover waste heat from the exhaust of a 7 ton boiler at the SAMEN Company (medicine production). By using the thermosyphon heat exchanger, 143,560 m^3 of natural gas will be saved and 281,990 kg production of CO_2 will be reduced per year. The pay back period from saving natural gas is 1.6 years.

*Received by the editors June 9, 2002 and in final revised form December 28, 2003
**Corresponding author

2. TWO-PHASE CLOSED THERMOSYPHON HEAT EXCHANGER

Heat exchangers made of a two-phase closed thermosyphon are one of the most effective pieces of equipment for waste heat recovery. A thermosyphon heat exchanger consists of a number of these tubes arranged in rows. THE's operate with the evaporator section of the thermosyphons in the high-temperature fluid stream and the condenser section in the low-temperature fluid stream. Heat transfer in a THE can be augmented by the addition of external fins to increase the surface area available for convective heat transfer (Fig. 1).

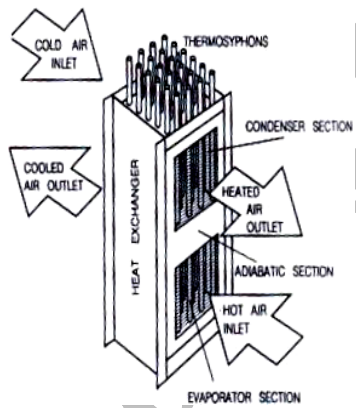


Fig. 1. Typical thermosyphon heat exchanger

The major advantages of THE's compared to conventional heat exchangers are that they are nearly isothermal and can be built with better seals to reduce leakage. THE's can serve as compact waste heat recovery systems which require no power, have a low pressure drop, and are easy to install on existing lines [11].

3. COMPUTER SIMULATION OF THERMOSYPHON HEAT EXCHANGER

In order to simulate the THE, all the related formulae and equations have been used in a computer program. The method adopted in the present study for prediction of heat transfer performance of THE is based on the effectiveness-number of transfer units [14]. In the following analysis, the water thermosyphons are considered to be in a staggered arrangement with continuous aluminum finned circular tubing. Also, the LMTD method is described and compared to the previous method.

The steps in the simulation of THE require the determination of the following factors:

1- Surface characteristics. This factor includes:

   Selection of a type of heat exchanger.

   Arrangement of tubes and specification of fins.

2- Fluid properties, (flue gases and cold air inlet)

3- Reynolds number: $\mathrm{Re}_L = \frac{GS_L}{\mu}$

4- Reynolds-Colburn factor: $j = 0.195\,\mathrm{Re}_L^{-0.35}$

5- Heat-transfer coefficient: h

6- Overall coefficient of heat transfer: $U_t = \frac{1}{R_t}$

   where $R_t = (R_{e,o} + R_{e,p} + R_{e,i} + R_{vapor} + R_{c,i} + R_{c,p} + R_{c,o})$

   The resistance network shows the total thermal resistance in the thermosyphon (Fig. 2).

7- Outlet temperatures and heat transferred:

   Effectiveness-number of transfer units (ε-NTU) method:

$$NTU = \frac{U_t A_t}{C_{\min}}$$

$$\varepsilon = 1 - \exp(-NTU) = \frac{T_{h,in} - T_{h,out}}{T_{h,in} - T_{c,in}} \qquad \Rightarrow \qquad T_{h,out} = specified$$

Log-mean temperature difference method (LMTD):

$$\dot{Q} = U_t A_t \Delta T_m$$
$$\dot{Q}_h = \dot{m}_h c_{p,h} (T_{h,in} - T_{h,out})$$
$$\dot{Q}_c = \dot{m}_c c_{p,c} (T_{c,out} - T_{c,in})$$

There are three equations with three unknowns, $\dot{Q}$, $T_{h,out}$, $T_{c,out}$, which must be solved simultaneously.

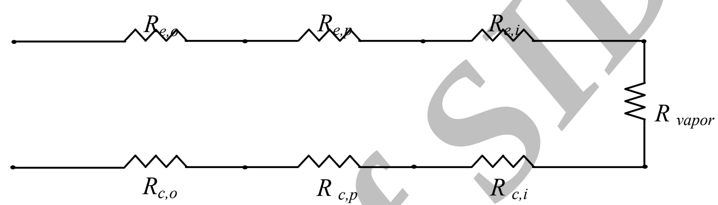


Fig. 2. Total thermal resistance in the thermosyphon

The two methods of THE analysis each have specific advantages and disadvantages. The ε-NTU method is the more direct, but requires simplifying assumptions in the expression for the effectiveness. The LMTD does not have these simplifications, but often requires an iterative solution procedure based on estimated temperature distribution.

4. ANALYSES AND INSTALLATION OF THERMOSYPHON HEAT EXCHANGER

In order to burn the fuel as completely as possible, it is better to mix the fuel and the air in the boiler as quickly and homogeneously as possible. Therefore, preheating the incoming air could raise the combustion efficiency and fuel consumption could be reduced. There are many ways to preheat the incoming air. The usual way is to install a heat exchanger, which utilizes the waste heat from the exhaust gas. A gas-to-gas thermosyphon heat exchanger was simulated in this research to recover waste heat from Boiler No.1.The operating data for Boiler No.1 are shown in Table 1.

Table 1. The operating data for the Boiler before using the THE

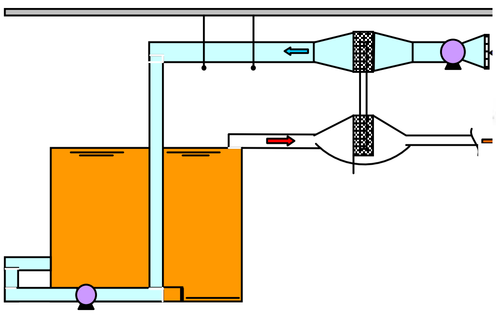
1- Specification of Boiler • Size: ≈ 7 tons • Electric Power : 26 kW • Efficiency : ≈ 85% • Chimney height : 12m • Duct size: Ø 535 mm **2-The properties of the exhaust gas:** • Temperature: 220 ± 20°C • Volumetric flow rate: 1.15 m³/s • Density : 0.732 kg/m³ • SO_X: < 2 PPM	**3-Output steam pressure:** 10 kg/cm² **4-The properties of the incoming ambient air:** • Temperature: average 30°C in summer and 15°C in winter • Volumetric flow rate: 1.58 m³/s (maximum) **5-The properties of the fuel used:** • Fuel type: Natural gas • Temperature: 30°C • Fuel consumption rate : 520 m³/hr • Caloric value of gas : 8200 kcal

As seen in the table, since fuel is natural gas (NG), the exhaust consist of less than 2 ppm SO_X. With this assumption, the dew point for sulfuric acid in the exhaust gas is between 70 to 100 °C. The physical dimensions of simulated thermosyphon heat exchanger in the heat recovery unit are shown in Table 2.

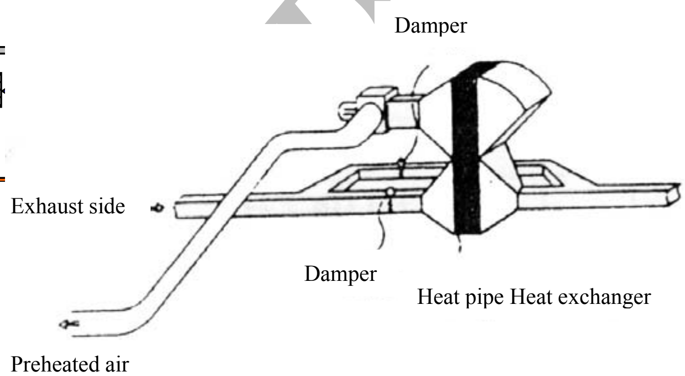
The thermosyphon heat recovery unit is installed such that the evaporating section of the thermosyphon is in the exhaust side and the condensing section of the thermosyphon is in the incoming ambient air side. As shown in Fig. 3, a bypass in the exhaust side is used to adjust the volume flow rate of the exhaust gas. By doing this, the temperature of the exhaust gas of the thermosyphon heat exchanger can be controlled above the dew point of sulfuric acid (70~100 °C).

Table 2. The physical parameters of the thermosyphon heat exchanger

Physical dimension of the heat exchanger	130(Height) × 83(Length) × 43(Width) cm
Physical dimension of each thermosyphon	D_o=25.4 mm D_i=23.4 mm L_{tube}=120 cm
Type and dimension of Fins	Aluminium plate fin, thickness = 0.4 mm Number = 96 m-1, Spacing = 10 mm
Heat pipe arrangement	Staggered, S_L=50 mm, S_T=55 mm
Row number of the thermosyphons	N_L = 7 N_T = 15
Total number of the thermosyphons	105
Thermosyphon material and its working fluid	Copper - Water



(a)



(b)

Fig. 3. The schematic descriptions of (a) the thermosyphon air preheater unit for the boiler, and (b) the heat exchanger and the bypass arrangement

5. RESULTS AND DISCUSSIONS

a) Temperatures and heat recovery

To avoid corrosion by sulfuric acid, the thermosyphon air preheater as a heat recovery unit was simulated to lower the temperature of the exhaust gas from 220 °C to a temperature above 100 °C. Hence the exchanger can:

1. Reduce the exhaust temperature from 220°C to 140°C,
2. Preheat the incoming ambient air from 25°C to 100°C with an exhaust mass flow rate of 1.15 m³/s.

With the simulated parameters the thermosyphon heat exchanger can recover energy about 100 kW.

b) Fuel saving rate and efficiency

According to the operating conditions of the boiler, after installation of a thermosyphon heat recovery unit, the fuel saving rate can be calculated as [6]

$$x = \frac{w \times c_p \times \Delta T}{Hg} \times 100\%$$

With the mass and energy balance for this boiler and using Excel Software, the air weight needed to burn $1Nm^3$ of fuel is:

246887.1 (grmol/hr) × 29 (gr/grmol)=7159725.9 (gr/hr)=7159.73 (kg/hr)
7159.73 (kg/hr) ÷ 580 (m³/hr) = 12.34 (kg air / 1 m³ fuel) ⇒ w = 12.34 kg

The average temperature of the incoming ambient air is 25 °C, the specific heat, c_p, is about 0.24 kcal/kg.°C. Therefore, when $\Delta T \geq 95$ °C, the fuel saving rate can be calculated

$$x = \frac{12.34 \times 0.24 \times 95}{8200} \times 100\% \cong 3.4\%$$

The original efficiency of the boiler was 85% before the installation of the heat pipe recovery unit, hence the boiler efficiency after the installation of the heat recovery unit can be calculated using the following equation:

$$\eta' = \frac{\eta}{(1-x)}$$

Therefore with a fuel saving rate of 3.4%, the boiler efficiency of the thermosyphon heat recovery unit after installation will be about 87.99%.

Fuel saving per year: $0.034 \times 580 (m^3/hr) \times 20 \times 364 = 143560\ m^3$ NG
CO_2 reducing production per year:

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O$$

$$\{143560\ m^3 \times 44\ (kg/kgmol)\} \div 22.4\ (m^3/kgmol) = 281990\ kg \cong 282\ ton$$

c) Pay back period

The purpose of investing in heat recovery is to get the net profit as high as possible compared to the total expenses related to the investment. Although the technical effectiveness of the heat recovery system is an important factor in gaining interest from potential customers, almost every customer analyzes the investment and maintenance cost of the system before purchasing it. Technically the task in heat recovery is to recover the maximum possible heat energy from the flue gases by the simplest solution. The payback period of the heat recovery system at the SAMEN company is based on the following two costs:

1-Annual reduction of fuel cost

The company operating hours = 20 hours per day, 7 days a week, 52 weeks per year.
The yearly reduced natural gas consumption for the boiler = 143560 m^3 NG
The cost of natural gas = \$ 0.03/ m^3
The annual fuel cost reduction = \$ 4300

2-Initial investment cost

The total cost of the THE heat recovery system installed at the company is estimated as follows:

The total price for one THE (manufacture and supply of heat exchanger including pressure test and cleaning) = \$6,000
Air ducts and fittings (including the labor, insulation and material)= \$1000
Total investment cost for the waste heat recovery system = \$ 7000

From the above calculations, an estimation of the payback period for the initial capital investment with respect to the annual fuel cost reduction is = Initial investment cost / Fuel cost reduction = \$ 7000 ÷ \$ 4300 = 1.6 years. Therefore, it is estimated that the simulated heat exchanger system would require about 1.6 years to payback. In addition, the average life span of the heat exchanger is estimated at about 10 years. Hence, the deduced payback period is quite acceptable.

6. CONCLUSIONS

A gas-to-gas themosyphon heat exchanger was successfully simulated for energy recovery from the exhaust of a 7 ton boiler at the SAMEN Company. It was found that:

1. The application of thermosyphon heat exchangers, as waste heat recovery systems in the SAMEN Company, would be a very good example for other suitable industrial plants to utilize this technology for recovering their waste heat.
2. From the simulation, it was found that the system operates very well, with an average thermal effectiveness of about 40%, and the average heat recovery from the flue gases 100 kW.
3. By using the thermosyphon heat exchanger, 143,560 m^3 natural gas will be saved and 281,990 kg production of CO_2 will be reduced per year.

4. The payback period is less than two years, which is reasonable, compared to the average life span of the thermosyphon heat exchanger.

NOMENCLATURE

A	total heat transfer area
C	capacity-rate (dimensionless)
c_P	specific heat of the ambient air
G	mass velocity of exchanger stream
Hg	8200 kcal/ m³ (caloric value of gas)
j	St $Pr^{2/3}$
$\dot{m}$	mass flow rate
NTU	number of heat transfer units
Q	heat transfer rate
R	thermal resistance
Re_L	Reynolds number
S_L	longitudinal distances
η	efficiency of boiler before the installation of the heat recovery unit
η'	efficiency of boiler after the installation of the heat recovery unit
ΔT	the temperature difference of the incoming air raised by the heat pipe heat recovery unit
T	temperature
U	overall heat transfer coefficient
w	air weight needed to burn $1Nm^3$ of fuel
x	fuel saving rate
μ	viscosity
ε	effectiveness of exchanger

Subscript

c	condenser
e	evaporator
i	inside
o	outside
p	pipe wall

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