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Design and Thermal Performance Study of a Heat Pipe Heat Exchanger

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Abstract: This paper describes a theoretical approach to design of a heat pipe heat exchanger. The analysis is based on Ntu-effectiveness approach to deduce heat transfer characteristics of the heat exchanger. In this study the variation of overall effectiveness of heat pipe heat exchanger relative to the heat capacity ratio (C_e/C_c) is presented and an optimum number of rows of heat pipes on thermal performance of exchanger were determined.

Keywords: Heat pipe, Heat recovery, Heat exchanger, Effectiveness, Evaporator and Condenser.

طراحی و مطالعه عملکرد حراتی یک مبدل حرارتی لوله‌گرمائی

عزت‌الله آزاد - پژوهشکده مواد پیشرفته و انرژی‌های تجدیدپذیر- سازمان پژوهش‌های علمی و صنعتی ایران

چکیده: این مقاله رویکد نطری طراحی یک مبدل حرارتی لوله‌گرمائی را توصیف می‌کند. تحلیل براساس رویکرد NTU- ضریب تأثیر قراردارد که منتج به تعیین مشخصه‌های حرارتی مبدل حرارتی می‌گردد. در این مطالعه تغییرات ضریب تأثیر کلی مبدل حرارتی لوله‌گرمائی برحسب نسبت ظرفیت‌های حرارتی (C_e/C_c) ارائه می‌شود و تعداد بهینه ردیف لوله‌های‌گرمائی برای حداکثر عملکرد حرارتی مبدل تعیین می‌شود.

واژه‌های کلیدی: نانوسیال، شبیه‌سازی عددی، کانال عمودی، جابجایی آزاد و اجباری.

1. Introduction

The function of an air heater in a modern fossil fired boiler plant is to absorb substantial quantities of waste flue-gas heat and transfer the heat to cooler air flow and, therefore, to increase the furnace combustion- air supply temperature.

A variety of equipment for heat recovery process exists such as heat wheels, plate fin heat exchangers and heat pipes [1-6]. Fig.(1) shows a typical classification of heat recovery systems. The heat pipes are relatively newcomers to the field of heat transfer, and its full potential is yet to be appreciated. Heat pipe is ideally suited for many waste heat recovery applications because of their ability to act as thermal impedance isothermal surface. Heat pipe units can provide design flexibility when waste heat recovery systems are planed, and they can be applied when retrofitting to existing systems.

This paper presents a design study of heat pipe heat recovery for preheating the furnace combustion-air supply.

2. The Heat Pipe

A heat pipe as shown in Fig.(2) is a closed container with small amount of working fluid. Heat is picked up at one end of the heat pipe (evaporator) and fluid evaporates at that end. The vapour flows towards the other end of the heat pipe where it is cooled and condenses (condenser), giving up its latent heat of vaporization. The liquid returns to the evaporator either by capillary action or simply by gravity. The vapor pressure drop between the evaporator and condenser is very small, so that evaporating/condensing cycle is essentially an isothermal process. Fig. (2) shows schematic diagram of a heat pipe.

3. System Description

This work is concerned with the design of a gas-to-air heat pipe heat exchanger using circular finned heat pipes as the heat transfer element, the system is shown in Fig.(3).

This type of heat exchanger offers many advantages over the conventional of heat exchangers. The advantages are summarized as follows:

- Redundancy - Leaks in one pipe, for instance, does not affect the operation of the rest of the heat pipes.
- Compact - High heat transfer surface area per unit volume; simple ducting requirement;
- Reliable – No moving parts; no external power required; each heat pipe is individually sealed;
- No contamination – Sealed divider separates two flow streams;
- Minimum Maintenance – No worn parts or seals to be replaced; easy to clean.

This paper presents an analytical study of the performance of effectiveness-Ntu approach to deduce its heat transfer characteristics of a HPHE.

4. Analysis

A schematic of the system is shown in Fig.3. Assuming the axial heat conduction through the heat pipes walls is negligible, the following equations for steady-state operation of heat recovery can be written:

a) For evaporator sections:

$$R_{eo} = \frac{1}{\eta_{eo} h_{eo}} \tag{1}$$

$$R_{ep} = \frac{t_p A_{eo}}{k_p A_{ei}} \tag{2}$$

$$R_{ew} = \frac{t_w A_{eo}}{k_w A_{ei}} \tag{3}$$

$$R_{ei} = \frac{A_{eo}}{h_{ei} A_{ei}} \quad (4)$$

Where, resistances are based on outside total area of evaporator sections.

b) For condenser sections:

$$R_{ci} = \frac{A_{co}}{h_{ci} A_{ci}} \quad (5)$$

$$R_{cp} = \frac{t_p A_{co}}{k_p A_{ci}} \quad (6)$$

$$R_{co} = \frac{1}{\eta_{co} h_{co}} \quad (7)$$

The overall heat transfer coefficients are:

$$U_e = (R_{eo} + R_{ep} + R_{ew} + R_{ei})^{-1} \quad (8)$$

$$U_c = (R_{co} + R_{cp} + R_{ci})^{-1} \quad (9)$$

Convection heat transfer coefficient for air normal to staggered circular finned tube bank is given by [7].

$$Nu = 0.314\, Re^{0.681} \left(\frac{s_f}{L_f}\right)^{0.2} \left(\frac{s_f}{t_f}\right)^{0.11} \quad (10)$$

Equation (10) can be used for bank tubes six-row deep. Fig. (11) of ref. [8] is used to correct for banks of other than six-rows.

5. Exchanger Effectiveness

In the evaporator section of a single row heat pipe, the hot fluid is in cross flow with vapour flow inside the heat pipes. However, since the vapour inside the heat pipe is almost at constant temperature, its specific heat, C_P, and capacity rate, C_L, become by definition, equal to infinity and as a result $(C_e/C_L) = (C_c/C_L) = 0$, therefore, the effectiveness-NTU equations for a single row heat pipe heat exchanger are as follows [1].

a) For evaporator sections:

$$\varepsilon_{e1} = 1 - exp(-Ntu)_{e1} \quad (11)$$

$$\varepsilon_{c1} = 1 - exp(-Ntu)_{c1} \quad (12)$$

b) For condenser sections:

Overall effectiveness of a single row is written as:

$$\varepsilon_r = \left[\frac{1}{\varepsilon_{e1}} + \frac{C_e}{C_{c1}}\right]^{-1} \quad \text{if } C_e < C_c \quad (13)$$

$$\varepsilon_r = \left[\frac{1}{\varepsilon_{c1}} + \frac{C_c}{C_{e1}}\right]^{-1} \quad \text{if } C_c < C_e \quad (14)$$

The overall effectiveness of heat recovery with N rows can be written as:

$$\varepsilon_0 = \frac{1 - \left[\frac{1 - C^* \varepsilon_r}{1 - \varepsilon_r}\right]^N}{C^* - \left[\frac{1 - C^* \varepsilon_r}{1 - \varepsilon_r}\right]^N} \quad (15)$$

Where $C^* = (C_{min}/C_{max})$

6. Case Study

A heat pipe heat exchanger is to be designed for a fired heater. Hot exhaust gas enters the evaporator section of exchanger at $260^{\circ}C$ with a flow rate of 10.2 kg/s and cold air at $27^{\circ}C$ is entering the condenser section. The purpose of heat pipe heat exchanger is to raise the air temperature to about $100-130^{\circ}C$.

In this design heat pipe condenser length (airside) is shorter than evaporator length (gas side). There are two reasons for this. Firstly, the flue gas pressure drop must be minimized to preserve a negative pressure in the top of the furnace. Secondly, since the combustion air is clean, more fins per meter can be utilized than can be considered for the flue gases side, thereby increasing the air side heat transfer effectiveness.

The design temperature for the current system has been selected as 300 ^{o}C, a higher temperature should be considered to allow for possible air temperature rises. Three working fluids have been evaluated for the range of temperature between 250-350 ^{o} ; namely, water, Dowtherm A and mercury. Dowtherm A has a low surface tension and poor latent heat of vaporization; mercury as a working fluid in heat pipes is toxic, expensive and difficulty is encountered in wetting the wick and the wall of the heat pipe. Water was selected as working fluid within this range. The selection of water was based on state of the art technology, its good transport properties, economic considerations and its non-toxic nature. However, it is not compatible with mild or stainless steel, as non-condensable gases can be generated within the heat pipe and therefore must be used with copper containment vessel. Copper, however, becomes rapidly annealed above $200^{o}C$ and therefore can not withstand the internal pressure. By cladding a copper tube with stainless steel tube, a heat pipe can be constructed [9].

Bienert of Dynatherm Corporation [10] has investigated the compatibility between water and corrosion resistant type 347 stainless steel; the result shows that stainless steel is compatible with water as a working fluid. The method adopted for prediction of the thermal performance of a heat recovery system is based on the NTU-effectiveness approach as described. Fig.(4) shows variation the effectiveness vs. the number of rows for different values of design parameter, C^*. Fig.(5) shows the variation of flue gases and air temperatures against number of rows for different values of C^*. By examination of Fig.(5) it is revealed that for a heat exchanger with 6-rows (in order to increase the air temperature by 100 ^oC, the outlet air and exhaust gas temperature can reach (for maximum air flow rate i.e.C^*= 0.97) to 120 ^oC and 170 ^oC respectively, for C^* = 0.96. The pressure drop for both sides is given in Fig.6. The general arrangements of the system are shown in Fig.7 and 8 and detail of design process are listed in table (1).

7 Conclusion

A heat pipe heat exchanger was designed using heat pipes as energy recovery devices. The heat pipes efficiently extract waste heat from flue gases and its temperature reduces from 260^{o}C to 170^{o}C and transfers it to an air flow and hence increases its temperature from 27^{o}C to 120^{o}C. The heat pipe heat exchanger is a flexible unit which can be used in many installations where its convenience makes it superior to other possible design solutions. In addition, the use of heat pipes eliminates services, additional moving parts, extra ducting and construction work.

Nomenclature

A	Area, (m^2)
C	Capacity rate, ($W.\ K^{-1}$)
C_L	Heat pipe working fluid capacity rate, (W,K^{-1})
Cp	Specific heat capacity, ($J.\ kg^{-1}.K^{-1}$)
h	Heat transfer coefficient, ($W.m^{-2}.K^{-1}$)
k	Thermal conductivity, ($W.m^{-1}.K^{-1}$)
L	Length, (m)
N	Number of rows
N_f	Number of fins per meter
NU	Nusselt number
NTU	Number of heat transfer units
Pr	Prandtl number
Re	Reynolds number
S_f	Fin spacing,(m)
S_L	Tube spacing in flow direction, (m)
S_T	Tube spacing cross to flow direction, (m)
T	Temperature, (K)
t	thickness, (m)
U	Overall heat transfer coefficient, ($W.m^{-2}.K^{-1}$)
η	Fin efficiency

Subscript

c	Condenser
e	Evaporator
o	Outside, overall
p	Pipe
r	Row
f	Fin
i	Inside

7. References

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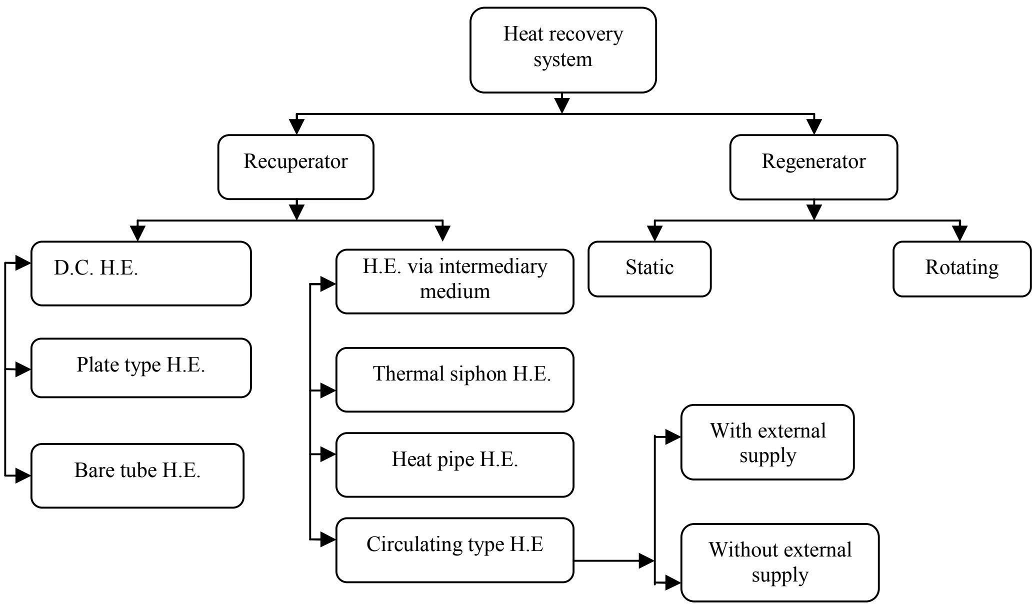

Fig. (1): Classification of heat recovery system

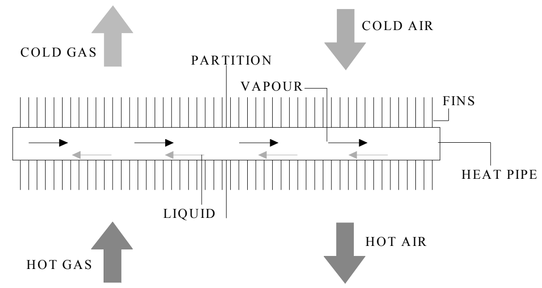

Fig. (2): Layout of a heat pipe.

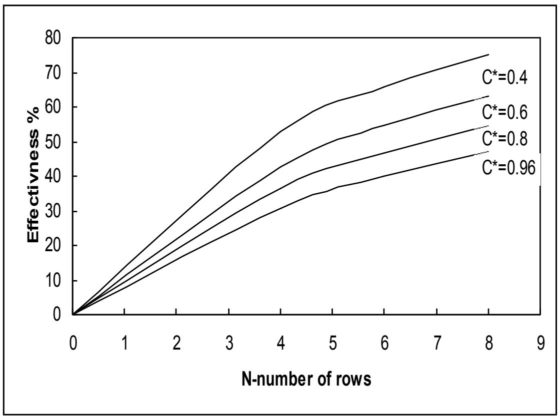

Fig. (4): Effectiveness Vs number of rows for different values of C*

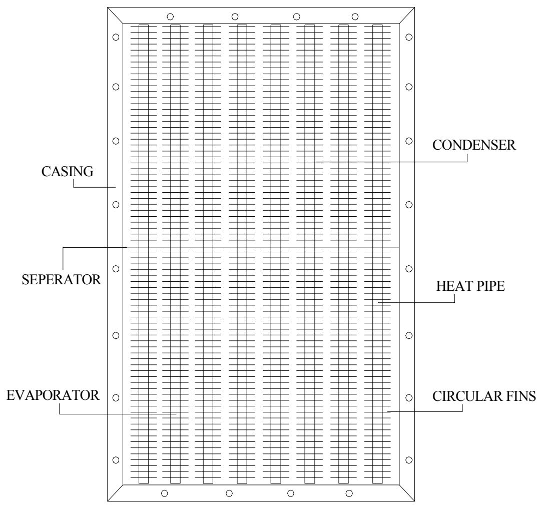

Fig. (3): Heat pipe heat exchanger

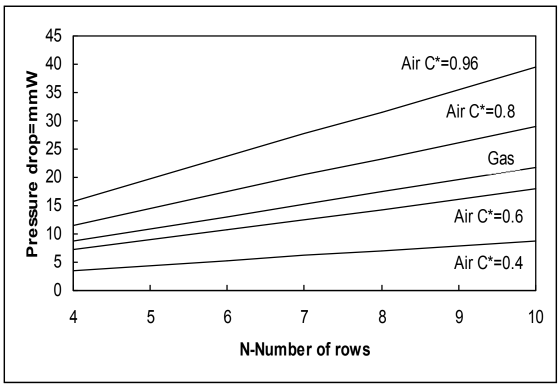

Fig. (5): Outlet air and gas temperature Vs number of rows

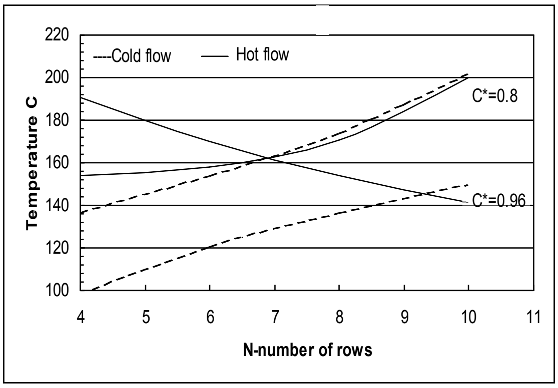

Fig. (6): Gas and air pressure drop Vs number of rows

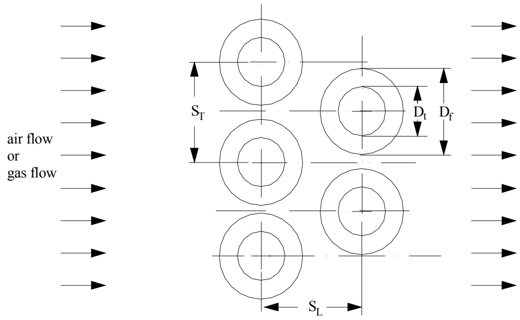

Fig.(8): Arrangement of heat pipes in heat exchanger

Table (1): Heat pipe heat exchanger design parameters

Design parameter	Value	Unit
Flue gas flow rate	10.2	Kg/s
Flue gas inlet temperature	260	^oC
Air inlet temperature	27	^oC
Number of pipes in a row	14	
Number of rows	6	
Total number of heat pipes	84	
Pipe size (O.D.)	51	mm
Pipe wall thickness	2.41	mm
No. of fins (air side)	240	/m
No. of fins (gas side)	120	/m
Tube spacing (Normal to flow)	105	mm
Tube spacing (flow direction)	111	mm
Evaporator length	2.74	m
Condenser length	1.83	m

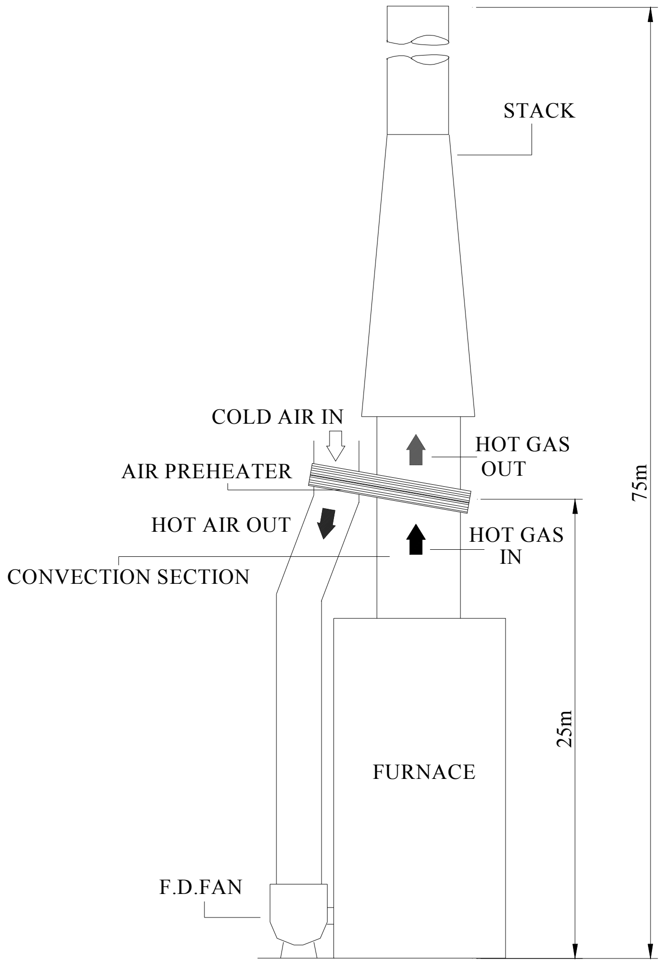

Fig. (7): Front view of solar collector assembly