HEAT PIPE HEAT EXCHANGERS USED IN WASTE HEAT RECOVERY SYSTEMS

UNGUREANU VIRGIL-BARBU *, HORNEȚ MIRCEA **

*University TRANSILVANIA of Braşov, Department of Mechanical Engineering
**University TRANSILVANIA of Braşov, Department of Civil Engineering

Abstract. It is presented an applied brief study concerning the possibility of heat pipe heat exchanger utilization in waste heat recovery systems and there are emphasized advantages of this kind of heat exchanger. A numeric comparison is carried out in order to prove the superiority of the forced convection heat transfer for fluids passing across pipes, like both regions of the heat pipe.

Keywords: heat pipe, heat pipe heat exchangers, waste heat recovery, convection heat transfer, fluid velocity.

1. INTRODUCTION

The basic heat pipe is a closed container which has evacuated of all non-condensable gases and which contains a capillary wick structure and a small amount of vaporizable fluid [1]. The heat pipe employs a boiling-condensing cycle and the capillary wick pumps condense to the evaporator. This is shown schematically in figure 1.

The essential components of a heat pipe are the sealed container, a wick and a suitable working fluid in equilibrium with its own vapour. When heat is applied along one section of the heat pipe (evaporator), the local temperature is raised slightly and part of the working fluid evaporates. Because of the saturation condition this temperature difference results in a difference of the vapour pressure which, in turn, causes vapour to flow from the heated section to a cooler part of the heat pipe (condenser). The rate of evaporation is commensurate with heat absorbed in the form of latent heat of evaporation. During steady state operation, the conservation of energy principle requires that the amount of heat absorbed is identical to the heat released. Return of the liquid condense occurs through the wick.

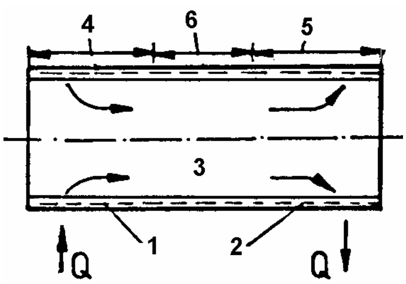

Fig. 1. Heat pipe:
1 – wick ; 2 – liquid ; 3 – vapor ;
4 – evaporator zone ; 5 - condenser zone 6 – adiabatic zone.

The heat pipe operating temperature ranges are: cryogenic (0 to 150K), low temperature (150 to 750 K) and high temperature (750 to 3000 K). Working fluids are usually elemental or simple organic gases in the cryogenic range, mainly polar molecules or halocarbons (with some restrictions) and liquid metals in the high temperature range.

The vapor pressure drop between the evaporator and the condenser is very small and, therefore, the boiling-condensing cycle is essentially an isothermal process. Furthermore, the temperature losses between the heat source and the vapour and between the vapour and the heat sink can be made small by a proper design. Therefore, one feature of the heat pipe is that it can be designed to transport heat between the heat source and the heat sink with very small temperature losses.

In the body forces field the condense returns to the condenser section without a wick. But the wickless gravity assisted heat pipe contained the disadvantage that the condense returns against the vapour flow and establish the entrainment limit. However, the low cost of the gravitational wickless heat pipes determines its utilization in industrial applications.

2. MODERN CONCEPTS CONCERNING WASTE HEAT RECOVERY SYSTEMS

The principle scheme of a heat pipe heat exchanger is presented in figure 2.
Generally speaking, it can distinguish four established main systems actually used for waste heat recovery heaving various temperature levels [1]:

- coil and tube heat exchangers;
- heat recovery systems with smooth steel pipes;
- heat recovery systems made by cast iron pipes with fins;
- flat plate heat exchangers;
- intermediate fluid heat exchangers;
- rotating type heat regenerators.

Given all of before heat exchangers, heat pipe heat exchangers have important advantages.

Because heat recovery installations represent always an "annex" for technologic installations it necessitates a small volume and high compactness, therefore an efficiently heat transfer. For this purpose it needs to use practical methods for heat transfer improvement [2], [3] and [4]. Because the largest waste heat is rejected having that support fluids in gaseous state and the heated fluid is air (knowing that these fluids have small convection coefficients) it needs an optimal design of the heat transfer surface, using some of the well-known means for heat transfer improvement: extension of heat transfer surface with fins, turbulence promoters and other. Among the before recovery heat exchangers just in the heat exchanger with intermediate fluid it can be realized a suitable extension of the heat transfer surface on both fluids path. At all others, the outer surface is inevitable bigger that the inner. Thus, it can be remarked the obvious advantage of heat pipe heat exchanger with finned outer surface on both fluids and a smallest internal heat resistance, practically negligible.
Figure 3 presents a heat exchanger with steel smooth pipes

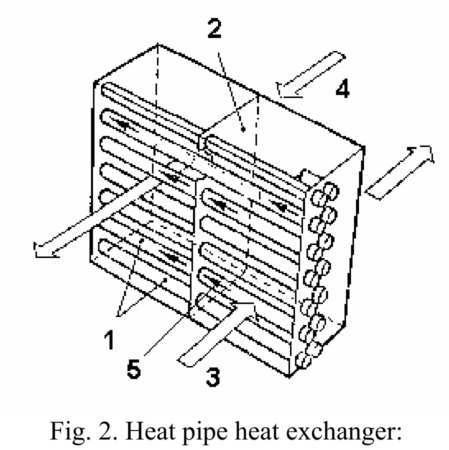

Fig. 2. Heat pipe heat exchanger:
1 – heat pipes; 2 – strainer plate; 3 – primary heat carrier; 4 – secondary heat carrier; 5 - heat transfer

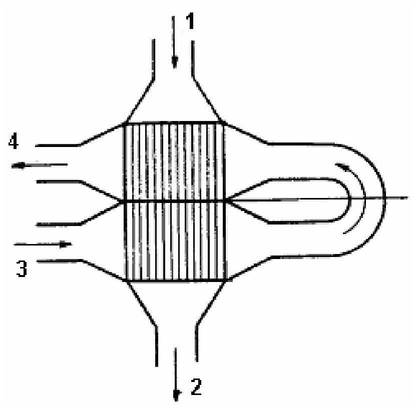

Fig. 3. Heat recovery heat exchanger with steel smooth pipes:
1 – waste gas input; 2 – waste gas output; 3 - cold air; 4 – warm air

In the case of burned gas overloaded with solid dust adherent to heat transfer surfaces, the finned pipes cannot be a viable solution. The surfaces in contact with waste heat carriers must to be smooth and easy cleaned. It can easily demonstrate that in the case of heat pipe with smooth surfaces too, its superiority is evident.

3. NUMERIC COMPARISON

Thus, for heat recovery made by smooth pipes, waste gas flow in pipes for a good cleaning. In the case of a turbulent regime the convection coefficient can be determined from Dittus-Boelter equation [3]:

$$\mathrm{Nu}_{f1} = 0{,}021 \cdot \mathrm{Re}_{f1}^{0{,}8} \cdot \mathrm{Pr}_{f1}^{0{,}3}. \qquad (1)$$

In the case of a bundle of pipes crossed by the gas flow it can be used the criterial equation of Kays [2]:

$$\mathrm{Nu}_{f2} = 0{,}33 \cdot \mathrm{Re}_{f2}^{0{,}6} \cdot \mathrm{Pr}_{f2}^{0{,}3}. \qquad (2)$$

It is considered the air forced convection for a heat exchanger having similar geometries, one with a bundle of pipes and the other with heat pipes.
For the 1st heat exchanger, the primary fluid (the hot) circulates in pipes and the secondary fluid cross, in a single pass on the outer surface of pipes. There are considered the follow values of heat exchanger parameters:

- mass flow rate of the hot fluid: $\dot{M}_1 = 0{,}1869\ \mathrm{kg/s}$;
- mean temperature of the hot fluid: $t_1 = 160{,}9\ °\mathrm{C}$;
- mass flow rate of the cold fluid: $\dot{M}_2 = 0{,}3703\ \mathrm{kg/s}$
- mean temperature of the cold fluid: $t_2 = 35{,}05\,°\mathrm{C}$;
- outer diameter of pipes: $d_e = 22\ \mathrm{mm}$;
- inner diameter of pipes: $d_i = 18\ \mathrm{mm}$;
- overall number of pipes: 90;
- number of pipes on a row: 9;
- utile length of pipes (there are excluded the strainer plates each considered half of the strainer plate of the heat pipe heat exchanger: 0.851m.

It results successively:

- hot fluid density: $\rho_1 = 0.7598\ \mathrm{kg/m^3}$;
- hot fluid mean velocity in pipes: $v_1 = 10{,}74\ \mathrm{m/s}$;
- cold fluid density: $\rho_2 = 1.07\ \mathrm{kg/m^3}$;
- hot fluid mean velocity in pipes: $v_2 = 3{,}3\ \mathrm{m/s}$;
- hot fluid dynamic viscosity $\mu_1 = 24{,}309 \cdot 10^{-6}\ \mathrm{m^2/s}$;
- Reynolds number of the hot fluid: $\mathrm{Re}_{f1} = 6042$;
- hot fluid thermal conductivity: $\lambda_1 = 3{,}53 \cdot 10^{-3}\ \mathrm{W/mK}$;
- Nusselt number of the hot fluid: $\mathrm{Nu}_{f1} = 20{,}15$;
- hot fluid thermal convection coefficient: $\alpha_1 = 39{,}5\ \mathrm{W/m^2K}$;
- cold fluid dynamic viscosity : $\mu_2 = 18{,}92 \cdot 10^{-6}\ \mathrm{m^2/s}$;
- Reynolds number of the cold fluid $\mathrm{Re}_{f2} = 4106$;
- cold fluid thermal conductivity: $\lambda_2 = 2{,}67 \cdot 10^{-3}\ \mathrm{W/mK}$;
- Nusselt number of the hot fluid: $\mathrm{Nu}_{f2} = 44{,}03$;

- cold fluid thermal convection coefficient: $\alpha_2 = 53{,}38\ \mathrm{W/m^2K}$.

It is observed a very small velocity of the secondary fluid (it necessitates to be at least twice), but that determine a convection heat transfer coefficient 35% bigger than the hot fluid convection coefficient. That fact in the condition of a cold fluid heat transfer surface area is 22% bigger than the hot fluid convection heat transfer area, and results a high difference between heat flux densities. Is important to mention that a disadvantage of small velocities is the dust deposition increasing.

Is very interesting to determinate the relation between the two fluids velocities in order to obtain equal heat flux densities. This case because length of both cylindrical heat transfer surfaces are equal, the relation is reduced to the equality of heat transfer coefficients (the pipe thickness is neglected):

$$\alpha_1 = \alpha_2, \tag{3}$$

that can be written:

$$0{,}021 \cdot \frac{\lambda_1}{d_i^{0,2}} \cdot \frac{v_1^{0,8} \rho_1^{0,8}}{\mu_1^{0,8}} \cdot \mathrm{Pr}_{f1}^{0,3} = 0{,}33 \cdot \frac{\lambda_2}{d_e^{0,4}} \cdot \frac{v_1^{0,6} \rho_1^{0,6}}{\mu_2^{0,6}} \cdot \mathrm{Pr}_{f2}^{0,3}. \tag{4}$$

From that it can be obtained the primary fluid velocity:

$$v_1 = 31.287 \cdot v_2^{0,75} \cdot \left(\frac{\lambda_2}{\lambda_1}\right)^{1,25} \cdot \frac{\rho_2^{0,75}}{\rho_1} \cdot \frac{\mu_1}{\mu_2^{0,75}} \cdot \frac{d_i^{0,25}}{d_e^{0,5}}. \tag{5}$$

Substituting problem data, it results:

$$v_1 = 15{,}65 \cdot v_2^{0,75}, \tag{6}$$

and finally:

$$v_1 = 38{,}33\ \mathrm{m/s}. \tag{7}$$

This value is too large and do not be accepted because the pressure loss increase on the primary fluid path.

The second variant for equilibrium between the two heat transfer coefficients can be the secondary fluids velocity decrease. Substituting the primary fluid velocity, $v_1 = 10{,}74\ \mathrm{m/s}$ in relation (6), it results:

$$v_2 = 0{,}605\ \mathrm{m/s}. \tag{8}$$

Practically, the primary flow rate being known, its velocity increasing can be realized by flow area decreasing, that is by number of pipes decreasing. But this method decreases the heat transfer surface and the heat exchanger does not satisfy the design parameters. The secondary fluid velocity can be decreased very simple by a bigger number of pipes on each row, at limits tje heat exchanger having a single row. But this method is a purely theoretic method for equilibrium of heat transfer coefficients and cannot be a method for heat exchanger optimization.

4. OTHER ADVANTAGES

All above being mentioned, we can say that the forced convection heat transfer when the fluid flows across pipes is much efficiently than inner pipes. In the case of heat pipes, the convective heat transfer to and from it are realized only on external surfaces therefore is very efficient. Moreover, in many cases because different flow rate or properties of both fluids that carried-out the heat transfer, the convection heat transfer coefficients are different, but the heat pipe offers the possibility to equilibrate heat flux densities by adopting different lengths of both zones: evaporation and condensation. This case, it is used the fundamental property of the heat pipe named heat flux density transformer: for the lower heat flux density is offered a higher heat transfer surface area.

Thus it still results a great advantage of the heat pipe heat exchanger: high compactness, therefore small volume and low materiel consumption. Heat pipe heat recovery has a great ratio between heat transfer surface and volume. This domain, it vies only with plate heat exchangers.

All rotating heat regenerators cannot realize a good tightness between heat carriers. In the case of the conventional heat exchanger it is a single wall between the two heat carriers, he liable to wear. It can be corroded and pursuits to leakage detectable only with gas analyzers or increasing of absorbed power of fans. The repair can be made function of the type of heat exchanger: for those with pipes the corrosion zone is situated in the cold corners and can be remedied in the 1st variant by forced introducing a sort pipe inner pipe, but this method have the disadvantage of the pressure loss increasing and in the 2nd variant by the total replacement of the heat exchange; for the plate heat exchangers can be used only the 2nd variant. At the heat pipe heat exchangers the heat transfer unit (heat pipe) can be fixed in the middle plate by relative easy way and relies a good tightness. in the case of an unit damage by corrosion appear a pore on the side of a heat carrier on where the working fluid gets out. But it is a small chance that the same heat pipe has still a pore, therefore the tightness of the heat pipe heat exchanger is very good.
It seems that the heat exchanger with intermediate fluid has the same advantage but if loses the quantity of fluid and it out of run.

In order to detect the damaged heat pipes at the heat pipe heat exchanger it can measure the temperature of the heat pipe in the end cap of the condenser zone. If it is low, near the cold fluid temperature, it carries out only the replacement of the damaged heat pipe, which necessitates shot time stand-bye of the technological process. Moreover, heat pipe heat exchangers can be realized with an adiabatic zone visible, out of the installation and comprised between the two zones of the heat pipes. This solution can be used in the case of pure fluids heated with waste heat carriers. The transport zone becomes a sanitary protection zone.

In the case of classic heat exchangers, any damage determines a drastic decreasing of the assembly performances and imposes the out of run and renounces the heat recovery in the most case.

In the case of heat exchangers with intermediate fluid the circulation is realized aided by a pump and at the rotating regenerators the movement of heat transfer surface between both heat carriers is realized by an electric motor. Thus, both cases it is reduced the reliability of the system given the passive heat pipe heat exchanger.
The high reliability is another advantage of the heat pipe heat exchanger. If few of heat pipes are out of run, the performances of the system are not perturbed essentially and no jeopardize its working. All elements can be substituted: heat pipes, strainer plate, or guiding plates from end caps, remaining all the running order heat pipes.

All heat recovery heat exchangers are endowed with especial devices for dilatation. The expansion bends are expensive and increases the heat recovery installation cost. There are used commonly methods but there are not realize a reliable sealing. On the other hand, the heat pipe heat exchanger has a good behavior at dilatation: heat pipes are free end caps and can dilate without any working incident.

Given heat exchangers with intermediate fluid for that fluid circulation is realized aided by a pump and heat regenerators for that the hat transfer surface rotation is realized with an electric motor, the operating expenses for heat pipe heat exchangers are the lower. It is not an additional cost for energy because the heat transfer is carried-out by the temperature difference between the two zones of the heat pipe.

In the case of especial applications, for example those of the heat, ventilation and acclimatization it needs that the sense of heat transfer between heat carriers is reversible for the two seasons: winter and summer. For the heat exchanger with intermediate fluid this reason is realized naturally. But the wick less gravity heat pipe works that a thermal diode, irreversible. By incline angle change that heat pipe can to work reversible, the two zones, vaporization zone and condensation zone change its roles. Thus, these kinds of heat pipes can transfer the heat in both directions function of the position of the heat source from that the recovery is realized.

For the fluid flowing in the pipes it is the tendencies of dust falls that creates problems in all heat exchanger working process. In the caase of heat pipe heat recovery systems is practical eliminated this difficulty. However, corrosions and depositions of outer heat pipe surfaces remains in the case of heat pipe heat exchangers. But the outer zones of the heat pipe being free, (the heat pipe is fixed in a median position in the strainer plate) can be easy cleaned with a tubular brush connected at an vacuum cleaner. Thus, the access at the heat pipe heat transfer surfaces is simplified and the cleaning time is reduced.

The working service time of heat pipe heat exchangers is long if it is correctly designed and manufactured.

In the heat exchanger design, the primary fluid cooling is stopped in the vicinity of the exhaust gas condensation point, these being an obligatory limitation. It needs a raised wall temperature of the hot heat transfer surface especially in the unpropitious zones. But, from the before theoretical calculus the forced heat convection coefficient of the cold fluid is higher than the hot fluid one and the heat transfer surface temperature is nearly of the cold fluid one and promote the dew-point reaching. At the heat pipe heat exchangers right designed, it can obtain that the heat pipe working temperature is the average between the two heat carrier temperatures. Thus, it can be realized an advanced heat recovery without the heat pipe damage. The flexibility in working and the possibility to replace only the failed units are other advantages of this kind of heat exchangers even in the case of the accidental dew point reaching, for example in the low ambient temperature.

By an adequate design [1], [4], a heat pipe heat exchanger realized with fractioned condenser zones can use two fluids that absorb heat from one waste source.

Apparently it is a single disadvantage of the heat pipe utilization> the internal heat resistance between the two heat carriers. But practically this resistance is very low, negligible than the forced heat convection resistances of both heat carriers because of the very high coefficients of boiling – condensation processes carried out inner the heat pipe.

5. CONCLUSION

For all the aforementioned advantages it appreciate that the heat pipe heat recovery systems will become one of the most efficiently from the thermal and economic point of view. The heat pipe heat exchangers can be manufactured from fined or smooth pipes and have high heat transfer coefficients, small volume and weight, high flexibility, reliability, maintenance, low consumption of working energy and can be easy cleaned.

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