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# DESIGN AND ANALYSIS OF HEAT PIPE HEAT EXCHANGER EFFICIENCY

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# КОНСТРУКЦИЯ И АНАЛИЗ ЭФФЕКТИВНОСТИ ТЕПЛООБМЕННИКА

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*Abstract.* The heat pipe has a high thermal conductivity, and its basic working principle is to transfer heat through evaporation and condensation through the working medium inside the pipe. Heat pipe has good thermal conductivity, isotherm and other characteristics, and the heat transfer area at both ends can be changed at will, control the temperature and other advantages. Therefore, the heat pipe heat exchanger has the advantages of high heat transfer efficiency, compact structure, small fluid resistance loss, and beneficial to control dew point corrosion. At present, it has been widely used in metallurgy, chemical industry, oil refining, boiler, ceramics, transportation, light textile, machinery and other industries, as energy saving equipment for waste heat recovery and heat energy utilization in the process, and has achieved remarkable economic benefits. The design of the heat pipe heat exchanger on the development of the current situation, development trend, application, design principle and design process of a simple description, while focusing on the discussion of the heat pipe heat exchanger design process. The main content of the heat exchanger thermodynamic calculation, structural design and material selection. The model of heat pipe heat exchanger is established according to the actual situation and the calculated data.

*Аннотация.* Теплопровод обладает высокой теплопроводностью, и его основным принципом работы является передача тепла через рабочую среду в трубопроводе путем испарения и конденсации. Теплопровод имеет хорошую теплопроводность, изотермы и другие характеристики, а площадь теплопередачи на обоих концах может быть произвольно изменена, контрольная температура и другие преимущества. Таким образом, теплообменник трубки имеет преимущества высокой эффективности теплопередачи, компактной конструкции, небольшой потери сопротивления жидкости, что способствует контролю коррозии точки росы и так далее. В настоящее время широко используется в металлургической, химической, нефтеперерабатывающей, котельной, керамической, транспортной, легкой и механической промышленности, как процесс рекуперации остаточного тепла и использования тепловой энергии энергосберегающего оборудования, достигли значительных экономических выгод. Краткое описание состояния проектирования, тенденций развития, применения, принципов проектирования и процесса проектирования теплообменников с тепловыми трубами с уделением особого внимания процессу проектирования теплообменников. Основные элементы включают тепловые вычисления теплообменника, конструкцию и выбор материала. На основе фактических и расчетных данных была разработана модель теплообменника.

*Keywords:* heat pipe, heat exchanger, thermal calculation, structure design, material.

*Ключевые слова:* тепловые трубы, теплообменники, тепловые вычисления, конструкция, материал.

Due to incomplete equipment and other reasons, the utilization rate of resources such as coal has always been low. At the same time, the large amount of smoke generated during boiler combustion and the accompanying heat emissions into the environment can cause energy waste and environmental pollution, such as the greenhouse effect. Therefore, improving equipment in coal industry life, reducing flue gas temperature and recovering energy is an important way to improve resource utilization. For the coal industry, it is imperative to replace traditional heat exchangers with gas gas heat pipe heat exchangers. Because heat pipe heat exchangers can increase the air temperature of the boiler and preheat the fuel in advance to improve energy efficiency. At present, gas gas heat pipe heat exchangers are increasingly receiving attention from modern industrial development, and are applied in various industrial waste heat recovery and utilization systems, achieving energy-saving and emission reduction effects. However, due to technological limitations, heat pipe heat exchangers are still unable to become the main force of heat exchangers. Therefore, it is hoped that heat pipe heat exchangers can have greater breakthroughs in the industrial field.

This design is mainly based on the actual operation of the boiler and the actual conditions of flue gas waste heat recovery and utilization in China to design a specific plan. According to the initial parameters of flue gas flow rate, flue gas inlet and outlet temperature, and the use of air as a heat transfer means for recovery. Assuming that the boiler is at full load, a heat exchanger is designed to preheat the air to 130 ℃ at an inlet temperature of 30 ℃. Considering conditions such as flue gas corrosion, scale cleaning, and economy, the remaining heat that the heat exchanger can recover is calculated. Design the main structure and thermal calculation of a heat exchanger using the waste heat of a 200000 cubic meter flue gas.

The basic data is as follows: flue gas flow rate: V01=20000 $Nm^3/h$; Flue gas inlet temperature: t'1=200 °C; Flue gas outlet temperature: t "1=150 °C; Air inlet temperature: t'2=30 °C; Air outlet temperature: t "2=120 °C.

Choose a heat pipe gas-air heat exchanger based on the comparison of its economy and characteristics. For a heat pipe, temperature, working fluid, and material are the three major influencing factors on the performance of the heat pipe working fluid. Therefore, before designing, it is necessary to reasonably determine these three factors. This heat pipe adopts gravity heat pipe, with the same length of evaporation section and condensation section. The outer diameter of the heat pipe is 25 mm and the inner diameter is 21 mm.

Heat pipe temperature [1]: The temperature of steam in the steam chamber of a heat pipe under normal pipe conditions. In design calculations, the temperature of the heat pipe can be determined by the qualitative temperature of the flue gas and the qualitative temperature of the air.

$$t_v = (t_{m1} + t_{m2}) / 2 = 125℃ \quad (1)$$

The selection of heat pipe working fluid is mainly based on the working temperature. The working fluids used at different temperatures are different. And each working fluid is only suitable for the temperature range of the process. However, there are multiple working fluids available at the same temperature range, so it is necessary to choose the appropriate working fluid. The following Table 1, 2.

Table 1

HEAT PIPE WORKING MEDIUM AND ITS TEMPERATURE WORKING TEMPERATURE

| *Name* | *temperature range/℃* | *Heat transfer capacity per cm of heat pipe, Kw/cm* | *Name* | *temperature range/℃* | *Heat transfer capacity per cm of heat pipe,Kw/cm* |
|---|---|---|---|---|---|
| $H_2$ | -259 | | methane | -45~120 | |
| $N_2$ | -205~-170 | 0.8 | ethanol | -25~170 | |
| methane | -180~-120 | 2.2 | water | 5~220 | 19.0 |
| ethane | -130~-30 | 2.2 | Dowtherm A | 150~320 | 1.9 |
| propane | -150~80 | | Hg | 190~550 | |
| Freon-13 | -120~-20 | 0.8 | K | 400~800 | 320 |
| Freon-23 | -120~-20 | 1.6 | Na | 600~1000 | 1000 |
| Freon-22 | -9040 | 1.6 | Li | 1000~1500 | 1150 |
| $NH_3$ | -60~60 | 8.0 | Ca | 1100~1900 | 1600 |
| Freon-21 | -50~90 | 1.6 | Ag | 1500~2000 | |

Estimate the temperature inside the pipe using the following formula:

$$T_v = \frac{t'_1 + nt''_2}{1+n} \tag{2}$$

In the equation; T'1— flue gas inlet temperature, T'2 — water side outlet temperature. When the fluid involved in heat exchange is water, n is taken as 3-4, and when it is an organic fluid, n is taken as 2-3, resulting in a calculated TV=140. Similarly, the flue gas outlet TV= 60 can be obtained. This design uses water as the working medium, and the working temperature of water is within 5-220, which meets the requirements [2].

The main materials of the heat pipe are the shell, suction core, and working fluid. The basic principle of material selection is that materials must be chemically compatible.

Table 2

COMMON HEAT PIPE MATERIALS
AND WORKING FLUIDS WITHIN A WIDE TEMPERATURE RANGE

| *Structural materials* | *Working medium* | *Temperature，℃* | *Lifetime, h* |
|---|---|---|---|
| SS | $N_2$ | -200~80 | |
| SS | Freon | -100~0 | |
| SS, Ni, Al | $NH_3$ | -50~100 | |
| SS, Cu, Ni | $CH_3OH$ | -45~120 | |
| Cu, Ni | $H_2O$ | 100~250 | 7500 ($80^0$C) above 1000 (20~$120^0$C) |
| Ni, SS | K | 400~800 | |
| SS,Ni | Na | 600~1000 | |
| Nb-1Zr | | 1000~1300 | |
| Nb-1Zr | Li | 1100~1500 | |
| TZM-Mo | Li | 1400~1600 | |
| Ta, Ta-5W | Ag | 1500~2000 | |
| Re/W | In | 2000 | |

Select carbon steel with steel grade 20G (GB8163-86) as the material [3]，Required allowable stress at 200℃ [σ] = 123MPa, the maximum stress that can be borne inside the pipe is:

$$P_V = \frac{\delta_w \times 200[\sigma]}{d_0 - \delta_w} = 21.39 \times 10^6 \text{Pa} \quad (3)$$

In the equation: δ W — Pipe wall thickness, m; [σ] — Allowable stress, MPa; Pv — maximum allowable pressure inside the pipe, Pa; According to the table, the saturated steam pressure of water at 1600C is P=3.62 × 105Pa, PV>P, so the selected heat pipe wall thickness of 2 mm is appropriate, and the heat pipe job security.

This section mainly conducts heat transfer calculations for heat pipe gas-gas heat exchangers [4].

(1) Thermal properties parameters and heat release on the exhaust side. Average exhaust temperature:

$$t_{m1} = \frac{1}{2}(t'_1 + t''_1) = \frac{200+150}{2} = 175^\circ C \quad (4)$$

Tm: is used as a qualitative temperature to obtain the exhaust thermophysical parameters; Density $\rho_1$=0.799 kg/m$^3$; Specific heat $C_{p1}$ = 1.09 kj/(kg0C). Thermal conductivity $\lambda_1 =$3.792×10-2 w (m·℃). Viscosity $\mu_1 =$2.39×10-5 kg/(m·s). The density of exhaust gas under standard conditions is $p_{01}$ = 1.295 kg/m$^3$. The heat balance equation is:

$$Q = M_1 c_1 (t'_1 — t''_1) = M_2 c_2 (t''_2 — t'_2) \quad (5)$$

In the equation; M1, M2 — Mass flow rate of hot and cold fluids, Kg/s; $C_1$, $c_2$ — Specific heat of constant pressure mass of hot and cold fluids, J/(Kg. ℃);T "1, t" 1- inlet and outlet temperature of hot fluid, ℃,T "2, t" 2 — inlet and outlet temperature of cold fluid, ℃,Heat released by exhaust:

$$\begin{aligned} Q_1 &= \frac{\rho_{01} V_{01} c_{p1} (t'_1 - t''_1)}{3600} \\ &= \frac{1.295 \times 20 \times 10^4 \times 1.09 \times (200 — 150)}{3600} \\ &= 3920972 \quad \text{W} \end{aligned} \quad (6)$$

In the equation, $\rho_{01}$ — Density of flue gas under standard conditions, kg/m$^3$, $V_{01}$ — Volume flow rate of flue gas under standard conditions, m$^3$/h.

(2) Air side temperature rise and thermophysical parameters.

Depending on the situation, the heat dissipation loss rate ξ= 1%～5%。

Take a heat dissipation loss coefficient $\xi_0 =$ 3%.

Air heat absorption:

$$\begin{aligned} Q_2 &= (1 - \xi) \\ &= (1 - 0.003) Q_1 \\ &= (1 - 0.003) \times 3920972 \\ &= 3803342.84 W \end{aligned} \quad (7)$$

In the equation; ξ- Heat dissipation loss rate

Density of air under standard conditions: $p_{02} = 1.293$ kg/m$^3$
Average air temperature:

$$t_{m2} = \frac{t'_2 + t''_2}{2} = \frac{30+120}{2} = 75°C \quad (8)$$

Obtaining Air Thermophysical Parameters from Qualitative Temperature $t_{m2}$ and Look up Tables: density $p_2 = 1.0145$ kg/m$^3$

Specific heat $c_{p2} = 1.009$ kj/(kg$^0$C)

Thermal conductivity $\lambda_2 = 3.005\times10^{-2}$ W/(m·°C)

Viscosity $\mu_2 = 20.85\times10^{-6}$ kg/(m s)

Air flow rate:

$$V_{02} = \frac{Q_2 \times 3600}{c_{p2}\rho_{02}\Delta t_2} = \frac{3803342.8\times3600}{1.009\times1.293\times90} = 116609.99 \text{m3/h} \quad (9)$$

The average temperature difference refers to the average temperature difference across the entire heat exchanger. However, different averaging methods may have different names, such as arithmetic mean temperature difference, logarithmic mean temperature difference, integral mean temperature difference, etc. When analyzing the heat transfer temperature difference of a countercurrent heat exchanger, it is assumed that the mass flow rate of cold and hot fluids and the specific heat at constant pressure are constant; The heat transfer coefficient remains unchanged on the whole heat transfer surface: the heat exchanger has no heat loss; the axial heat conduction along the tube can be ignored. Based on the above assumptions, the formula for calculating the average temperature difference of the countercurrent heat exchanger is obtained:

$$\Delta t_m = \frac{\Delta t'' - \Delta t'}{In\frac{\Delta t''}{\Delta t'}}$$

This temperature is called the logarithmic mean temperature difference，$\Delta t_m$

$$\Delta t_m = \frac{\Delta t_{max} - \Delta t_{min}}{In\frac{\Delta t_{max}}{\Delta t_{min}}} \quad (10)$$

When the temperature changes little along the heat transfer surface, that is $\frac{\Delta t_{max}}{\Delta t_{min}} \le 2$, the arithmetic mean temperature difference can replace the logarithmic mean temperature difference:

$$\Delta t_m = \frac{\Delta t_{max} + \Delta t_{min}}{2} \quad (11)$$

The error is within the range of 4%, which is allowed by the engineering. The temperature difference between the two ends, and the heat exchanger is a countercurrent flow type:

$$\Delta t_1 = t'_1 - t''_2 = 200 - 120 = 80 \ °C$$

$$\Delta t_2 = t''_1 - t'_2 = 150 - 30 = 120\ °C$$

$$\Delta t_{max} = \Delta t_2 = 120°C$$

Logarithmic mean temperature difference:

$$\Delta t_{tm} = \frac{\Delta t_2 - \Delta t_1}{In\frac{\Delta t_2}{\Delta t_1}} = \frac{120 - 80}{In\frac{120}{80}} = 98.65°C \quad (12)$$

The selection principle of pressure vessel materials [5]: (1) container usage conditions, such as temperature, pressure, medium, operating conditions, and structural characteristics; (2) Mechanical properties of materials; (3) The corrosion resistance of the material; (4) Processing properties of materials, such as weldability, cold and hot processing formability, etc; (5) The price and source of materials; (6) The selection of materials in the same engineering design should be as uniform as possible. In this design, the material is 20G (GB8193-86) carbon steel; Operating temperature range: 0-350 °C; the design pressure is $P \leq 1.6$MPa; the thickness of the shell material steel plate is $t \leq 20$ mm.

Design temperature refers to the highest or lowest possible temperature that a container can reach on its shell wall or metal components under the corresponding design pressure in working engineering [2]. In this design, the design temperature is 146 °C, at which the allowable stress of 20G (GB8193-86) carbon steel is 10MPa, and the operating temperature range is -20 °C -450 °C. The design pressure corresponds to the design temperature and is used together as the design load condition. The design pressure of the evaporation and condensation sections in this design is both 0.10 Mpa.

Due to the design pressure of 0.1Mpa in this design, the thickness of the box is taken as 6mm, which is sufficient to meet the stiffness requirements. When the wall thickness is much smaller than the container wall thickness, and the diameter of the nozzle hole is not large, the working pressure is low, there is no need to open holes for reinforcement at this time.

Regulations: For heat exchangers used in industrial and general moderate process processes, the total thickness of any partition in the area of expanded pipes minus corrosion allowance shall not be less than 3/4 of the outer diameter of pipes with an outer diameter of 25.4 mm and smaller; For pipes with an outer diameter of 31.8 mm, it shall not be less than 22.2 mm; For pipes with an outer diameter of 38.1 mm, not only is it less than 25.4 mm; For pipes with an outer diameter of 50.8 mm, it is not only less than 31.8 m. For heat exchangers used in chemical processes, in addition to meeting the above requirements, it is also specified that the total thickness of the separator, excluding corrosion allowance, shall not be less than 19.1 mm.

In this design, the diameter of the shell is relatively large. If the thickness of the partition is too small, it may become unstable. Considering the minimum thickness requirement of the partition, the partition thickness is now taken as 30.0 mm.

The connection between pipelines adopts the form of extension sections. The hybrid structure of hard welding and expansion welding must meet two conditions [3]: the confidentiality of the connection ensures that the medium does not exit and the medium pressure is sufficient. According to the structure of the heat exchanger, the connection between the shell and the coated partition can be divided into two forms [5]: detachable connection and non detachable connection. To clean the pipeline, the ash in the carbon steel is removed, and a dust removal port is designed at the bottom. This design adopts a non detachable method.

Due to the fact that this design is for atmospheric pressure equipment, the wall thickness of the box is only 6mm, so the weight of the box is not very large. Based on economic analysis, the framework adopts 160×88×6mm I-beam. The support should bear the weight of the entire equipment and set anchor bolt holes to fix the equipment on the foundation, so adopt 200×102×9mm I-beam

In order to simplify the equipment structure and make it easy to manufacture, a symmetrical structure is adopted in the design. The smoke inlet and air outlet adopt the same size. The thickness of the inlet and outlet walls and the box body are uniformly selected with 6mm steel plates. To facilitate installation, first weld the panel and conical shell. In the front view, the conical shell is an isosceles trapezoid with a bottom angle of 775 °. Then, weld the connecting flange and finally weld it as a whole into the box.

Due to the rectangular structure of the box, traditional pressure vessel heads cannot be used. The sealing glaze of this design is also welded from I-beam and steel plate. Save materials and funds, and ensure consistency with the box structure, using a wall thickness of 6mm for the head. Considering maintenance and disassembly, the head and box are connected with bolt flanges.

This device is a waste heat utilization device for flue gas. Due to the tendency of finned heat pipes to accumulate dust and reduce heat transfer efficiency, a maintenance port needs to be set up on the box, which can be regularly opened and cleaned with a high-pressure water gun. The maintenance port is connected to the box using bolt flanges. For the convenience of detection, an inspection port is set up on the relatively clean air side with lower temperature. The size of the inspection and maintenance ports is the same, both 460 × 680 mm.

Heat pipe heat exchangers have significant advantages over other heat exchangers in terms of economy and heat transfer efficiency, and their structure is also simple. This article mainly focuses on the thermal calculation and simple structural design of heat pipe heat exchangers under certain conditions. Through relevant data, it further demonstrates the advantages of heat pipe heat exchangers in waste heat recovery, and provides a deeper understanding and mastery of heat pipe heat exchangers.

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