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Use of Waste Heat Using Heat Pipes

Kamil Sikora [1]

[1] Institute for Science and Research in the Field of Thermomechanics and Thermal Technology, Mongolská 1467/34, Ostrava Poruba, 708 00 Czech Republic

Abstract: The use of flue gas waste heat has been one of the most discussed topics in the field of energy management for a long time now. This is not only an economic question of wasteful use of the obtained heat, but also the ecological consequences caused by the increased amount of emissions, since most of the heat energy mankind still obtains is by burning fossil fuels. There are studies that try to prove that excessive burning of carbon can disrupt the balance of the planet's system, and according to some studies, it is the emissions of carbon dioxide produced by industry that cause the greenhouse effect, and the resulting increase in the temperature of the Earth's surface. Despite the fact that definitive proof of human influence on climate change has not been presented, thermal technology is a source of environmental pollution and efforts to mitigate the consequences of its action definitely have a place in planning the energy economy.

Keywords: Waste heat, heat exchangers, fossil fuels, flue gas, heat transport, energy management, heat pipes, ecology.

1. Introduction to the issue

Industry affects the environment by creating waste products, which can be in a solid, liquid, or gaseous state. In addition to direct and indirect air, water and soil pollution, the industry also affects its surroundings through thermal waste. The main goal of this article is the maximum use of the energy potential of waste heat and subsequently the reduction of specific fuel consumption in technological processes, by recalling an older discovery.

The use of waste heat using a combination of several technologies in one production unit is the only option to efficiently obtain waste heat. It is mainly about expanding the current usable temperature range of exhaust gases from the production process with the aim of heating domestic hot water (DHW), or energy production.

Another significant benefit will be the reduction of CO_2 emissions, as a result of the secondary reduction in fuel consumption. Air protection is one of the basic goals and tasks of environmental protection. The Czech Republic still ranks among the most polluted areas in Europe in terms of air pollution. The main cause of this situation is the high energy demand of the Czech industry, which exceeds the standards usual in developed countries, and consequently a large share of heat and energy production by burning low-quality fuels.

2. Heat exchangers

A heat exchanger (in general) is a device used to utilize the thermal potential of flue gases, which would otherwise end up as a chimney loss. Heat exchange between flue gas and water, or by gas, it takes place continuously – both media are separated from each other by a wall (tubes, slats, plates). According to the type of wall material, there are:

- *Metal.*
- *Ceramic.*

*** Corresponding author:** Kamil Sikora, ***E-mail address:*** *kamil.sikora@cylinders.cz*

According to the method of heat transfer, we divide them into:

- *Radiant.*
- *Convection.*
- *Combined.*

The use of heat in recuperators is limited by the wall temperature, which can be up to 700 to 800 °C for metal ones (alloyed heat-resistant steels must be used for higher temperatures), up to 1 000 °C and higher for ceramic ones. This also gives the maximum temperature of the flue gas before the recuperator, or heated air or gas behind the recuperator. For metal recuperators, the flue gas temperature is max. 800 °C, air heating is 300 to 500 °C, for ceramic recuperators the max. flue gas temperature is 1 200 to 1 400 °C, the air temperature is 850 to 950 °C. Of course, these values depend on the heat transfer parameters, especially on the heat transfer coefficients from the flue gas to the wall and from the wall to the air, respectively gas.

Heat exchangers can be classified according to the method of use, the number and arrangement of currents (co-current, countercurrent), the nature of heat exchange (without change or with phase change), or according to the number of heat exchange surfaces (mixing exchangers, where there are no heat exchange surfaces; regeneration exchangers with a single a heat exchange surface, which is alternately washed by a warm and cold stream, and recuperation exchangers, where the streams are separated by a heat exchange surface).

2.1 Heat balance

The heat balance expresses the efficiency of the heat source, and at the same time expresses the individual heat incomes and expenses, most often in the form of a percentage. The chemical heat, created by the burning of the fuel, passes partly into the material, partly into the flue gases, further into the walls of the furnace, and part escapes through leaks, which gives the furnace efficiency. The heat balance can be expressed simply according to the equation below:

$$Q_{ch} = Q_m + Q_{sp} + Q_z \quad \text{(J)} \qquad (1)$$

where: Q_{ch} is chemical heat of the fuel (J), Q_m - heat supplied to the material (J), Q_{sp} - the heat of the exhaust gases (J), Q_z - heat loss (J).

Graphically, the above heat balance equation is most often displayed using a Sankey diagram:

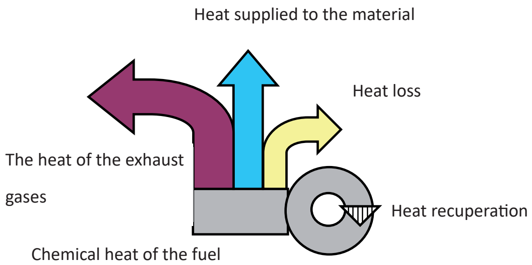

Figure 1: Sankey diagram.

It can be seen from the diagram that the chimney loss is often up to 30 % of the total chemical heat obtained by burning the fuel. Today's recuperators can return heat in the range of 800 to 400 °C to the work process. However, new technologies make it possible to obtain heat from 150 °C, which significantly reduces the percentage of heat in the flue gas.

3. Heat exchanger based on heat pipes

The solution is the use of waste heat using an exchanger based on heat pipes, which can be structurally very flexible. Heat pipes have many uses these days. It is primarily encountered in industry, where due to its enormous thermal conductivity, which is up to 1 000 times greater than that of a copper rod of the same dimensions, it is used to cool powerful electric motors, gas turbines, lasers, nuclear reactors, rocket engines and the like. By applying them, the temperature gradient of flue gases can be used even outside the current, commonly available range of 400 to 800 °C.

3.1 The principle of heat pipes

The first publication of the principle of heat pipes celebrates its 60th anniversary this year. Heat pipes are used to transfer heat from one place to another with the help of vapours of the working substance. It works on a very simple principle. It is a hermetically sealed metal cylinder that is filled with liquid. At one end it is inserted into the heat source and at the other into the heat sink. After reaching the temperature to which it is set, the working substance (ammonia, water, etc.) begins to evaporate and flows towards the cooled place, where it condenses. The vapour stream is set in motion based on the different pressures at the evaporator (higher pressure) and the condenser (lower pressure). The return of the condensate back to the heat source is ensured by capillary forces in the porous material, which transports the condensate back to the heat source.

This heat pipe allows it to work even in a position where the condenser is lower than the evaporator.

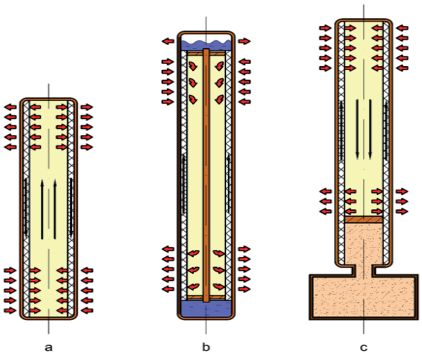

Figure 2: Principle of heat pipes.

The working temperature, that is the temperature at which the working substance begins to boil, is set by the pressure inside the heat pipe (thermosiphon). If we continue to talk about pressure, we will mean absolute pressure, it is calculated from zero (vacuum) and not from atmospheric pressure. The boiling point of a liquid is pressure dependent. For example, water, which can also be used as a working substance in a heat pipe, is 100 °C at atmospheric pressure. However, since the heat pipe is essentially a pressure vessel, this temperature often rises above 130 °C.

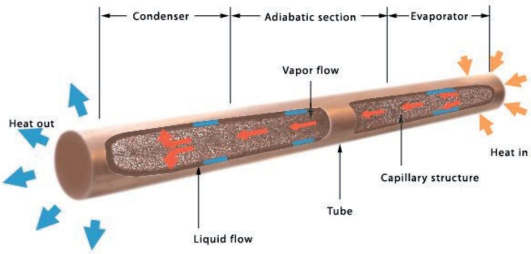

Figure 3: Thermal medium transfer diagram.

4. Calculation of the pressure loss of the exchanger

First, the pressure loss must be calculated by inserting a bundle of tubes into the flue gas channel so that the draft of the chimney is not compromised. The pressure loss through the insertion of a tube bundle varies according to the number of rows, columns, tube size and method of placement. This can be simulated using gas flow calculations. In staggered placement of the pipe system, we proceed from their location and mutual spacing.

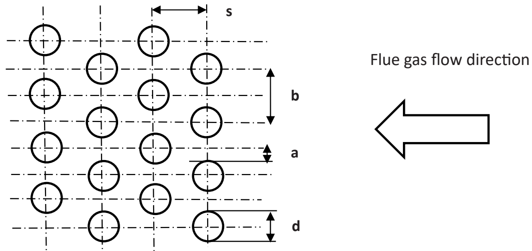

Figure 4: Tube storage schema.

Legend of Figure 4: s - distance of rows in the length of the exchanger, b - spacing of the first row, a - distance between the edge and the centre of the transplanted pipe, d - diameter of the pipe, n - number of rows in the length of the exchanger.

Solving the pressure drop Δp:

where: ζ is lost factor (1), v - gas velocity (m·s^{-1}), ρ - gas density (kg·m^{-3}), T - thermodynamic temperature (K), t - mean temperature: $\overline{t} = \frac{T_1 + T_2}{2}$.

The loss factor is calculated according to the formula:

$$\xi = 0.75 \cdot \left(n \cdot \frac{s}{b} \cdot \alpha + \beta \right) \quad (3)$$

where $$\alpha = 0.028 \cdot \left(\frac{b}{2a} \right)^2 \quad (1) \quad (4)$$

$$\beta = \left(\frac{b}{2a} - 1 \right)^2 \quad (1) \quad (5)$$

According to the procedure mentioned above, it is possible to change the number of rows n arbitrarily and thus simulate the pressure loss as needed by inserting a bundle of pipes of different diameters and numbers of rows in order to maintain the draft of the chimney.

5. Moderate temperature gradient

Another important parameter when assessing the energy justification of using a heat exchanger is the calculation of the average temperature drop. In counterflow, heat-carrying substances flow on both sides of the dividing wall. Heat is shared across the wall from the warmer fluid to the cooler, so the warmer fluid cools and the cooler warms. Let us observe a steady flow, during which the temperatures of the fluids are constant at every point of the surface, and let us neglect the heat loss.

In heat exchangers based on heat pipes, flue gas flows in one direction through a system of inserted tubes in the warm (lower) part of the exchanger, and cold water in the opposite direction through the upper part of the exchanger, where it takes the accumulated heat from the tubes.

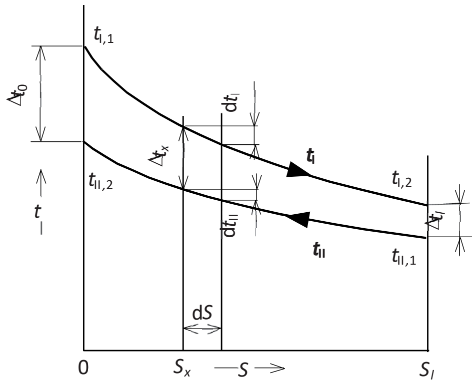

Figure 5: Temperature gradient.

Temperature is a function of streamwise length (one-dimensional temperature field). If the fluids do not flow parallel (cross-flow), the temperature changes in a direction perpendicular to the direction of the flow (two-dimensional temperature field).

The heat output from the warm fluid through the surface element dS to the cold fluid is given by the equation

$$dP = k \cdot (t_I - t_{II})_x \cdot dS \quad (W) \tag{6}$$

where: dP is heat flow (W), k - heat transfer coefficient (W·m^{-2}·K^{-1}), t - temperature (K), dS - heat exchange surface (m^2).

After equivalent adjustments and integration, we get the equation of the mean temperature difference, from which we can predict the theoretical heat output of the exchanger. This mean temperature difference is called the mean logarithmic temperature difference, and Δt_0 and Δt_l are the mean temperature drops at the beginning and end of the exchanger:

$$\overline{\Delta t_L} = \frac{(t_{I,1} - t_{II,2}) - (t_{I,2} - t_{II,1})}{\ln \frac{t_{I,1} - t_{II,2}}{t_{I,2} - t_{II,1}}} \quad (°C) \tag{7}$$

where: $t_{I,1}$ is temperature of the primary medium at the inlet to the exchanger (°C), $t_{I,2}$ - temperature of the primary medium at the outlet of the exchanger (°C), $t_{II,1}$ - temperature of the secondary medium at the inlet to the exchanger (°C), $t_{II,2}$ - temperature of the secondary medium at the outlet of the exchanger (°C).

6. Measurement on an industrial unit

The implementation of a heat exchanger in flue gas ducts tends to be very expensive, therefore, before the actual purchase of this device, it is necessary to carry out a series of measurements in operating conditions in order to be able to predict the economic and ecological consequences of this investment. For the needs of the heat balance, measurements were made of an industrial furnace for the heat treatment of metals, which already has a bypass built in the flue gas channel with a heat exchanger for hot water heating. The temperature of the furnace space, the temperature of the flue gas at the inlet and outlet to the heat exchanger, and the temperature of the domestic hot water at the inlet and outlet of the heat exchanger were measured. The measured parameters are shown in the following Table 1.

Table 1: Measured input parameters.

Time	*Furnace temperature*	*Flue gas tempe-rature outlet*	*Flue gas tempera-ture inlet*	*Water tempera-ture inlet*	*Water tempe-rature outlet*
hrs:min	°C	°C	°C	°C	°C
7:00	817	433	169	14	69
7:30	817	432	168	14	69
8:00	818	432	167	15	69
8:30	818	431	168	15	69
9:00	818	430	168	15	72
9:30	820	435	168	15	69
10:00	821	433	168	16	71
Diameter	818	432	168	15	70

A graph was compiled from the measured parameters, which show the course of the temperatures of the water circuit, i.e. the heat input of the exchanger. The temperature course for the inlet and outlet water is shown in the graph in Figure 6.

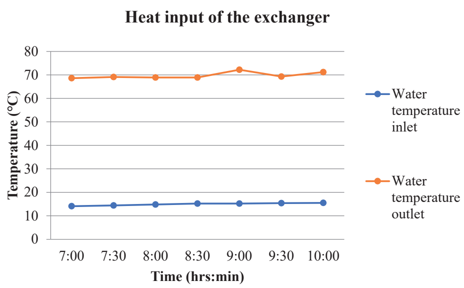

Figure 6: Course of DHW temperatures at the inlet and outlet of the heat exchanger.

6.2 The amount of heat given off by the flue gas

The amount of heat transferred is equal to the product of the mass flow of flue gas and the difference of the specific enthalpies of the flue gas for the inlet temperature and the outlet temperature of the flue gas. The inlet and outlet temperature of the flue gas is known by the specification from the company. For the next calculation, we need to find out the specific enthalpy of the input and output flue gases from the tables. For the average flue gas inlet temperature $t_{1,sp}$ of 432 °C, the specific enthalpy of 621 kJ·m^{-3} was determined from the tables. For an average outlet temperature $t_{2,sp}$ of 168 °C, the specific enthalpy from the tables was determined to be 257 kJ·m^{-3}.

$$P_{sp} = Q_{V,sp} \cdot \left(i_{sp,1} - i_{sp,2} \right) \quad \text{(W)} \tag{8}$$

where: P_{sp} is theoretical thermal input of flue gases (W), $Q_{V,sp}$ - flue gas volume flow (m^3·s^{-1}), $i_{sp,1}$ - specific enthalpy of flue gas at the inlet (kJ·m^{-3}), $i_{sp,2}$ - specific enthalpy of flue gas at the outlet (kJ·m^{-3}).

The volume flow of the flue gas, multiplied by the density, gives us the mass flow, so the result in Watts is: $P_{sp} = 1.78 \cdot 1.33 \cdot (621.1 - 257) = 861.97$ kW

The amount of theoretical heat input by flue gas is 862 kW.

6.3 Exchanger efficiency

The next step in the calculation of the proposal for the use of flue gas waste heat is the determination of the efficiency of the exchanger. The efficiency of the measured exchanger is calculated as the ratio of the amount of heat required and the amount of heat given off by the flue gas. From the volume flow of water using the same methodology as for flue gas, we find that the amount of heat needed to heat water P_w is 678 kW. Since the amount of heat transferred by flue gases is 862 kW, we obtain the measured efficiency of the exchanger by the ratio:

$$P_v = \frac{678.08}{861.97} \cdot 100 = 78.67\ \% \tag{9}$$

$$P_v = \frac{P_w}{P_{sp}} \cdot 100 \quad (\%)$$

The efficiency of the measured exchanger is 78.67%, which means that the heat loss of the exchanger is 21.33%.

6.4 Saving natural gas

The fuel for operating the furnace is natural gas with lower calorific value $Q_{i,g}$ = 35 880 kJ·m^{-3}, which means that the heat output is 9 966 kWh·m^{-3}. The last step will be the calculation of the amount of gas that will produce the necessary amount of heat.

$$Q_{CH} = Q_{i,g} \cdot V_g \quad \text{(J)} \tag{10}$$

where: Q_{CH} is chemical heat of the fuel (J), V_g - amount of gas (m^3),
which means:

$$V_g = \frac{678.08}{35.88} = 18.90 \quad (\text{m}^3). \tag{11}$$

$$V_g = \frac{Q_{CH}}{Q_{i,g}} \quad (\text{m}^3),$$

The saving of natural gas amounts to approx. 19 m3 per hour, which with continuous operation amounts to approx. 456 m^3 of natural gas per day. The secondary amount of reduction in CO_2 emissions can then be estimated from the empirical formula at about 5 000 m^3 per day.

6. Conclusion

Worldwide and permanently rising energy prices lead to a significant reduction in the consumption of all types of energy, especially thermal energy, in all industrial and non-industrial areas. The use of waste heat using exchangers saves fuel consumption and thus the environment. The obtained heat is either returned to the technological process, or is used to heat water and thus for further use. The previous chapters serve as a methodical guide to the initial calculations that must be carried out when considering the inclusion of a heat exchanger in the flue gas paths.

Obtaining thermal energy from flue gas is not a problem these days, the problem is to use this heat economically. The best way to use waste heat is to return it to the production process or use it to heat DHW. The inclusion of secondary heat exchangers in the existing flue gas channels is therefore a logical endeavour of all manufacturers using heat aggregates. Every fluid flow that involves heat sharing is associated with a pressure drop. There is a relationship between heat transfer intensity and pressure loss. The faster the heat exchange medium flows, the greater the heat transfer coefficient. This can be used to find the optimal geometry of the heat exchange surface.

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