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Counterflow step-type bulk material cooler

A S Shishkin[1, 2] and S F Shishkin[1]

[1] Department of equipment and automation of silicate productions of the Institute of new materials and technologies, Ural Federal University named after the First President of Russia B N Yeltsin, 19, Mira str., Yekaterinburg, 620000, Russia

E-mail: [2]a.s.shishkin@urfu.ru

Abstract. Counterflow cooling is extensively used in many industries to recover the heat from hot materials coming out of kiln. The method for calculating a counterflow step-type bulk material cooler is proposed. It is based on a matrix model of heat balance for individual cooling stages. The proposed equation system allows calculating the required number of steps and airing flow rate. The method was used to design a cyclone heat exchanger for an alumina calcination furnace and a counterflow louvered proppant cooler. It allows taking into account the degree of heat transfer incompleteness at individual stages and minimizing air flow for cooling. Examples of industrial introduction are given. The applicability of the method for counterflow heaters calculating is noted. On the basis of the offered method, step counterflow coolers with louvers were developed and introduced. Such devices and calculation methods can be used to heat the material before being fed into the furnace. The use of step-type counterflow heat exchanger makes it possible to utilize the heat of bulk material leaving the furnace and the heat of exhaust gases.

1. Introduction

In many industries, the task of cooling or heating bulk material is important. To obtain the maximum economic effect, it is advisable to use the heat of the exhaust gases and the thermal energy of the material leaving the furnace. Technically, this task is achieved through the installation of appropriate heat exchangers – heaters and coolers of bulk material. This approach allows saving fuel, increase productivity, i. e. creating efficient thermal installations.

A number of research papers have been published on energy analysis of the kiln heat exchangers in cement and alumina industry. Fans [1] has undertaken a study of clinker cooler efficiency. It is contented that the efficiency of the clinker heat exchanger depends substantially on the granulometry of the clinker. Rasul et al. [2] studied the thermal performance of a cement plant. They suggested using the exhaust gas leaving from kiln system for drying the raw material. Ziya et al. [3] have considered the operation of cement kiln system used in cement manufacturing. They proposed a mathematical model of new heat recovery exchanger to utilize the heat from the kiln system. Touil et al. [4] have applied the concept of exergy analysis to a clinker cooler of a cement production facility. Their research shows the importance of the inlet temperature ratio and the number of stages cross-current contacting. Taweel et al. [5] have reviewed an analysis of energy and exergy based on the clinker temperature profile. Their study allows predicting the temperatures of exhaust air and estimate of waste heat recovery from the clinker cooler system.

Another example is the cyclone calcination furnace for alumina production [6]. In this device, the heat of the exhaust gas is used to dry and heat the material entering the calciner. At the same time, air is used to cool the outgoing alumina, which passes through a four-stage countercurrent cooler, and then enters the combustion. Thus, heat losses with flue gases and output material are minimized. In dry cement kilns, four-stage cyclone heat exchangers are often used to heat a raw meal.

An important problem is the cooling of bulk material at low temperatures, for example from 300–200 °C to 80–70 °C. Consider this problem. An effective way to solve it is to implement a countercurrent stepwise cooling scheme. The design scheme of the cooler is shown in figure 1.

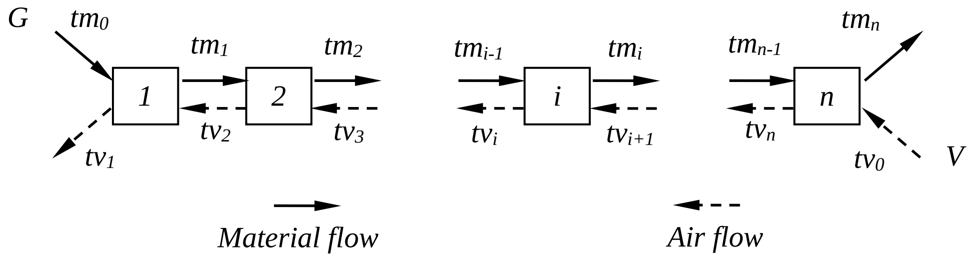

Figure 1. Design scheme of countercurrent cooler.

The following notation is used in figure 1: t_{mi}, t_{vi} – material and air temperatures at the exit of the *i-th* stage; $t_{mi\text{-}1}$, t_{vi+1} – the temperature of the material and air at the entrance to the *i-th* stage.

The material enters the first stage of the heat exchanger and moves in the direction of the last stage. Air enters the last stage of the cooler and moves counter currently in the direction of the first stage. Temperatures of the bulk material t_{m0} and air t_{v0} at the cooler inlet and also the flow rate of the bulk material G are known. It is necessary to calculate the air flow rate V, m^3/s, in order to provide a given final temperature t_{mk} of the bulk material at the outlet of the cooler.

2. The method of calculating the step-type counterflow heat exchanger

In the general case, specific heat of air c_v and bulk material c_m depend on temperature, therefore, the system of heat balance equations for n sections cooler will have next view:

$$\begin{cases} Gc_m(t_{m0})t_{m0} + Vc_{\mathrm{v}}(t_{v2})t_{v2} = Gc_m(t_{m1})t_{m1} + Vc_{\mathrm{v}}(t_{v1})t_{v1} + Q_1 \\ Gc_m(t_{m1})t_{m1} + Vc_{\mathrm{v}}(t_{v3})t_{v3} = Gc_m(t_{m2})t_{m2} + Vc_{\mathrm{v}}(t_{v2})t_{v2} + Q_2 \\ Gc_m(t_{\mathrm{m}2})t_{m2} + Vc_{\mathrm{v}}(t_{v4})t_{v4} = Gc_m(t_{\mathrm{m}3})t_{m3} + Vc_{\mathrm{v}}(t_{v3})t_{v3} + +Q_3 \\ \cdot \quad \cdot \quad \cdot \\ Gc_m(t_{\mathrm{mi\text{-}1}})t_{mi-1} + Vc_{\mathrm{v}}(t_{vi+1})t_{vi+1} = Gc_m(t_{\mathrm{m}i})t_{mi} + Vc_{\mathrm{v}}(t_{vi})t_{vi} + Q_i \\ \cdot \quad \cdot \quad \cdot \\ Gc_m(t_{\mathrm{mn\text{-}1}})t_{mn-1} + Vc_{\mathrm{v}}(t_{v0})t_{v0} = Gc_m(t_{\mathrm{mn}})t_{mn} + Vc_{\mathrm{v}}(t_{vn})t_{vn} + Q_n \end{cases} \tag{1}$$

The left side of each equation represents the heat input (enthalpy flux) to this section, the right side represents heat consumption, Q_i is the heat loss through the wall to the environment. For the cooler, at the first stage of calculations, it can be accepted that the heat capacity of the material and air is constant in a given temperature range, and heat losses can be neglected. The n equation system of heat balance for cooler sections will take next form:

$$\begin{cases} Gc_m t_{m0} + Vc_v t_{v2} = Gc_m t_{m1} + Vc_v t_{v1} \\ Gc_m t_{m1} + Vc_v t_{v3} = Gc_m t_{m2} + Vc_v t_{v2} \\ Gc_m t_{m2} + Vc_v t_{v4} = Gc_m t_{m3} + Vc_v t_{v3} \\ \cdot \quad \cdot \quad \cdot \\ Gc_m t_{mi-1} + Vc_v t_{vi+1} = Gc_m t_{mi} + Vc_v t_{vi} \\ \cdot \quad \cdot \quad \cdot \\ Gc_m t_{mn-1} + Vc_v t_{v0} = Gc_m t_{mn} + Vc_v t_{vn} \end{cases} \tag{2}$$

For fine bulk material, for example, alumina, the heat exchange process is completed quite quickly and it can be assumed that the temperatures of the material and air at the outlet of each stage are equal. For coarse bulk material, the heat exchange process doesn't have time to complete, and the following relation can be written for an arbitrary stage of the cooler:

$$t_{vi} = \eta t_{mi}, \tag{3}$$

where η is the coefficient of incompleteness.

The heat transfer incompleteness coefficient η for coarse bulk material is determined by calculation or experimentally for a specific device. Taking into account dependence (3), the equation system will take the form (4). This linear n equation system (4) contains n unknown material temperatures t_{m1}, t_{m2}, ... t_{mi}, ..., t_{mn}, and can be solved by any known method. Thus, the temperatures of the bulk material at the outlet of each stage will be found. Then, using relation (3), all air temperatures t_{v1}, t_{v2}, ... t_{vi}, ..., t_{vn} are found at the outlet of each stage.

$$\begin{cases} Gc_m t_{m0} + Vc_v \eta t_{m2} = Gc_m t_{m1} + Vc_v \eta t_{m1} \\ Gc_m t_{m1} + Vc_v \eta t_{m3} = Gc_m t_{m2} + Vc_v \eta t_{m2} \\ Gc_m t_{m2} + Vc_v \eta t_{m4} = Gc_m t_{m3} + Vc_v \eta t_{m3} \\ \cdot \quad \cdot \quad \cdot \\ Gc_m t_{mi-1} + Vc_v \eta t_{mi+1} = Gc_m t_{mi} + Vc_v \eta t_{mi} \\ \cdot \quad \cdot \quad \cdot \\ Gc_m t_{mn-1} + Vc_v \eta t_{m0} = Gc_m t_{mn} + Vc_v \eta t_{mn} \end{cases} \tag{4}$$

Let us introduce the following notation:

$$a = Gc_{\mathrm{m}}; \; \mathrm{b} = Vc_{\mathrm{v}}\eta; \; d = Vc_{\mathrm{v}}$$

Then, the equation system (4) consisting of a different number of stages will take the corresponding form. In the case of one stage, the temperatures of material and air at the cooler outlet are found by next dependences:

$$t_{m1} = \frac{at_{m0} + dt_{v0}}{a+b} \quad \text{and} \qquad t_{v1} = \eta t_{m1}$$

Two-stage cooler:

$$\left\{ \begin{bmatrix} -(a+b) & b \\ a & -(a+b) \end{bmatrix} \cdot \begin{bmatrix} t_{\mathrm{m1}} \\ t_{\mathrm{m2}} \end{bmatrix} = \begin{bmatrix} -at_{\mathrm{m0}} \\ -dt_{\mathrm{m0}} \end{bmatrix} \right.$$

Three-stage cooler:

$$\left\{\begin{bmatrix} -(a+b) & b & 0 \\ a & -(a+b) & b \\ 0 & a & -(a+b) \end{bmatrix} \cdot \begin{bmatrix} t_{\mathrm{m1}} \\ t_{\mathrm{m2}} \\ t_{\mathrm{m3}} \end{bmatrix} = \begin{bmatrix} -at_{\mathrm{m0}} \\ 0 \\ -dt_{\mathrm{v0}} \end{bmatrix}\right.$$

Further, it is not difficult to generalize to n steps. The temperatures of the material t_{m0} and the air t_{v0} at the inlet, as well as the matrix coefficients a, b, d are known. Having solved the system, the temperature distribution of the material at the cooler outlet of each stage can be found. The proposed model allows at the design phase to select the required number of a cooler stages and the required air flow to cool the material to the selected temperature.

3. Commercial tests

Based on this approach, several counter-flow bulk material coolers have been designed and are successfully operating for various tasks. As an example, a countercurrent cyclone alumina cooler on a cyclone calcination furnace [8] and a countercurrent louvered proppant cooler can be given. Consider these examples in more detail. Figure2shows a photograph that explains the principle of operation of a laboratory counterflow louver cooler. Material moves downward through inclined louvers, and air moves upward through the screens, cooling the material. Thus, a countercurrent three-stage cooling system is implemented. Figure 3 shows photograph of industrial counterflow louver proppant cooler operating at the factories of FORES LLC.

Determination of the required air flow for cooling and the number of cooler stages is performed using the proposed methodology. Figure 4 shows calculated final temperatures of the material and air at the outlet of the three-stage cooler, depending on the air flow. The temperature of material and air at the cooler inlet were set $t_{m0} = 250$ °C and $t_{v0} = -10$ °C, which corresponds to the data of industrial tests of a three-stage proppant cooler. The cooling capacity was $G = 17$ t/h. The temperature measurements for individual stages show that degree of incompleteness of the heat transfer process was $\eta = 0.8$. The material was supplied with a temperature of 240–270 °C and cooled to 77–90 °C. The air flow rate at the cooler inlet was $V = 15000$–15500 m^3/h. The air temperature at the cooler inlet was –10 °C. Calculated and experimental data are in satisfactory agreement with each other, as follows from the figure 4.

Figure 2. Counterflow coolers with louvers. The movement of the material in the laboratory model.

Figure 3. Industrial counterflow cooler with a capacity of 17 t/h.

Figure 5 shows the calculated graphs dependence of material and air temperature at the cooler outlet against the number of heat transfer stages. As follows from the graph, three stages are sufficient for cooling proppants under given conditions.

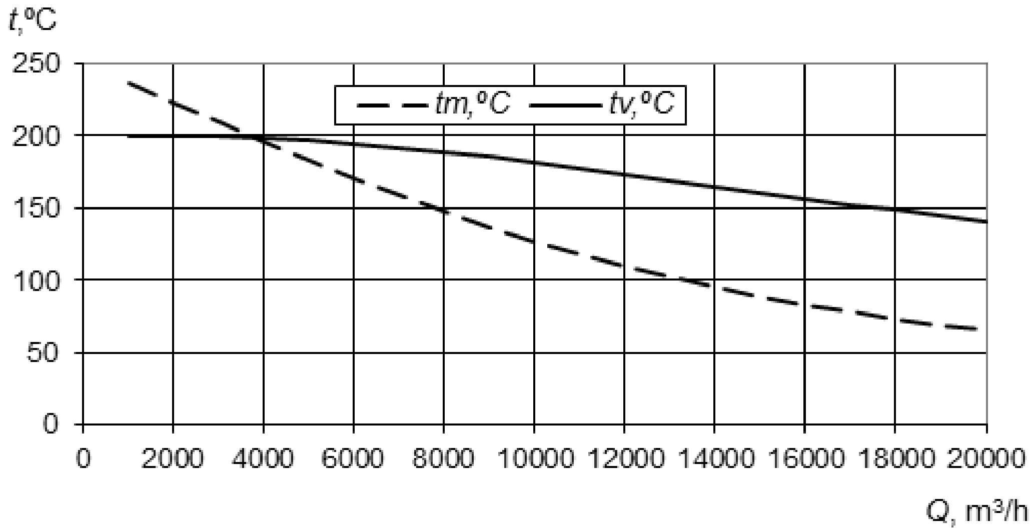

Figure 4. Air temperature at the cooler inlet t_{v0} = –10 °C, material t_{m0} = 250 °C, productivity *G* = 17000 kg/h, η = 0.8).

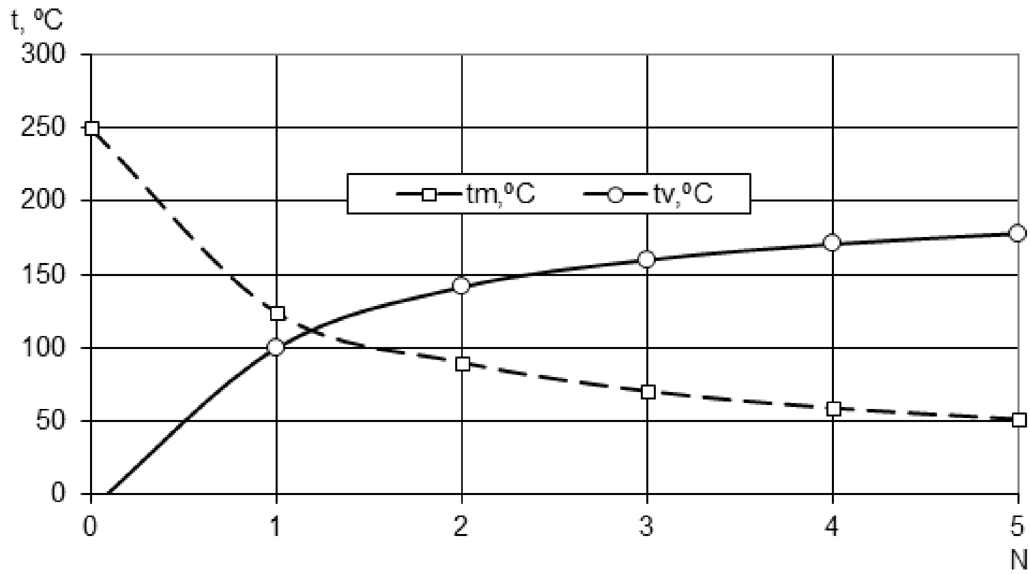

Figure 5. The dependence of material and air temperature at the cooler outlet against the number of heat transfer stages *N*. Air consumption *V* = 15000 m^3/h, G = 17 t/h, t_{m0} = 250 °C, t_{v0} = –10 °C, η = 0.8.

4. Conclusions

The proposed calculation method allows determining the required number of stages and air flow for cooling to the temperature setpoint. On the basis of the offered method, step counterflow coolers with louvers were developed and introduced. Such devices and calculation methods can be used to heat the material before being fed into the furnace. This will allow you to utilize the heat of the exhaust gases.

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