Recuperation of useful heat can be effected above all in continuous furnaces, in which heating of the material is not connected with subsequent industrial operations, as is the case for heating furnaces in forging units and rolling mills. Recuperation of useful heat can also be carried out in furnaces for the heating of liquids.

In batch furnaces, a constructive solution of the problem of heat recuperation is complicated and unprofitable.

At the present time, heat recuperation is being effected in rotating, shaft, and tunnel furnaces in the ceramics industry, and also in tubular and shaft furnaces for calcining ores.

The present article uses a graphical method, representing the heat in the form of a plane, in curves with the coordinates temperature-thermal capacity, to consider the utilization of fuel or heat in a tunnel furnace in the ceramics industry, the thermodynamics of countercurrent heat transfer, and heat recuperation processes. The treatment is carried through from the point of view of the first and second laws of thermodynamics, that is, in the present case, from the point of view of the heat balance and the required temperature-drops between the heating gases and the material.

A tunnel furnace consists, so to speak, of two heat exchangers, one of which has heating and calcining zones, and the other a cooling zone. They both work continuously in countercurrent heat transfer. It is further assumed that the masses of the material, \( G_m \), of the gases, \( G_g \), and of the cooling air, \( G_c \), remain unchanged during heating and cooling.

The heat transfer equation in both spaces of the furnaces has the form

\[
G_m C_m \frac{dT_m}{dt} = G_c \frac{dT_c}{dt} = G \alpha C \frac{dT}{dt}
\]

\[
\eta \left( t_{g,a} - t_{g,o} \right) = \eta \left( t_{m,f} - t_{m,o} \right)
\]

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\]

Fig. 1. Counter-current heat transfer diagram: a) at \( W_m < W_g \eta \); b) \( W_m > W_g \eta \).

Fig. 2. Effect of heat losses through the body of the furnace on the utilization of heat.

Fig. 3. Heat transfer diagram in the working space of a tunnel furnace without recuperation of useful heat.

Fig. 4. Diagram of recuperation of useful heat.

where \( G_m \) is the weight of the material; \( C_m \) is the heat capacity of the material; \( t_m \) is the temperature of the material (mean); \( Q_{1.f} \) is the heat losses through the body of the furnace; \( G \) in the working space \( G = G_g \) is the weight of the heating gases; in the cooling zone \( G = G_c.a \) is the weight of the cooling air; \( c \) is the heat capacity of the gases, \( c_g \) or of the air, \( c_a \); \( t \) is the temperature of the gases or of the air; \( \alpha_c \) is the heat transfer coefficient in the working space or in the cooling zone (with respect to an element of surface); \( F \) is the surface of the material in the working space or in the cooling zone; \( \Delta t \) is the temperature difference between the gases or the cooling air and an element of surface of the material.

Since in the working space the temperature of the material rises, while the temperature of the gases decreases (in the cooling zone, the reverse), the heat losses through the walls, \( Q_{1.f} \), have a positive sign (+) in the heating and calcining zones, and a negative sign (-) in the cooling zone. In a three-dimensional coordinate system, the furnace represents a constant-temperature field.

A continuous countercurrent furnace can work under two basic sets of conditions: the thermal capacity of the gases greater than the thermal capacity of the material, that is, \( W_g > W_m \) or \( W_g/\eta > W_m \); and the thermal capacity of the material greater than the thermal capacity of the gases, that is, \( W_m > W_g \) or \( W_m > W_g/\eta \). Here \( W_g = c_g G_g \); \( W_m = c_m G_m \); \( \eta \) is the efficiency of the working space.

Each of these sets of conditions offers different possibilities for utilization of the heat introduced into the working space. These conditions are applicable for all heat exchangers of the countercurrent type and, consequently, also for recuperation of the heat of the material in the furnace. The recuperation zones of the furnace differ from the calcining zone in that in them heat transfer takes place without combustion of the fuel.

Assuming that, in both cases, exactly the same amount of heat is introduced into the furnace in a period of time \( \Delta t \), we obtain

\[
Q_g = G_g [c_g] t_g a
\]

where \( Q_g \) is the heat introduced into the furnace by the gases; \([c_g] t_g \) is the mean heat capacity in the interval between the temperature of the surrounding medium and the adiabatic temperature of the gases, \( t_g.a \).