processes

Supplementary Materials

Steady Heat Conduction

In thermodynamics, we considered the amount of heat transfer as a system undergoes a process from one equilibrium state to another. Thermodynamics gives no indication of how long the process takes. In heat transfer, we are more concerned about the rate of heat transfer.

The basic requirement for heat transfer is the presence of a temperature difference. The temperature difference is the driving force for heat transfer, just as voltage difference for electrical current. The total amount of heat transfer Q during a time interval can be determined from:

$$Q=\int_0^{\Delta t} Q.dt \qquad \text{kJ} \tag{1}$$

The rate of heat transfer per unit area is called heat flux, and the average heat flux on a surface is expressed as q;

$$q = \frac{Q}{A} \qquad \text{W/m}^2 \tag{2}$$

Steady Heat Conduction in Plane Walls

Conduction is the transfer of energy from the more energetic particles of a substance to the adjacent less energetic ones as result of interactions between the particles.

Consider steady conduction through a large plane wall of thickness Δx = L and surface area A. The temperature difference across the wall is $\Delta T = T_2 - T_1$.

Note that heat transfer is the only energy interaction; the energy balance for the wall can be expressed:

$$Q_{in} - Q_{out} = \frac{dE}{dt} \tag{3}$$

For steady-state 0peration, $Q_{in} = Q_{out} = constant$

It has been experimentally observed that the rate of heat conduction through a layer is proportional to the temperature difference across the layer and the heat transfer area, but it is inversely proportional to the thickness of thelayer.

$$\text{Rate of heat transfer} = \frac{\text{(surface area) (temperature difference)}}{\text{thickness}} \tag{4}$$

$$Q_{\text{ conduction}} = -kA\,\frac{\Delta T}{\Delta x} \quad \text{W} \tag{5}$$

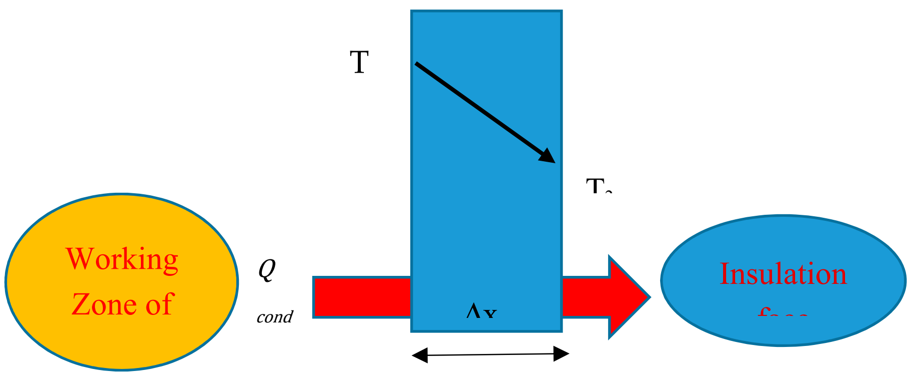

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Figure 1. Heat conduction through a large plane wall.(Resembling to the furnace heat shield).

The constant proportionality k is the thermal conductivity of the material. In the limiting case where $\Delta x \rightarrow 0$, the equation above reduces to the differential form:

$$Q_{\text{conduction}} = -kA\frac{dT}{dx} \quad \text{W} \tag{6}$$

which is called Fourier's law of heat conduction. The term dT/dx is called the temperature gradient, which is the slope of the temperature curve (the rate of change of temperature T with length x).

For the study case of furnace ,T1=1000 ° C and T2 =ambient temperature.

Thermal Heat Conduction in Cylinders (Furnace working zone)

Steady state heat transfer through cylindrical objects like a furnace shell/pipe, is in the normal direction to the wall surface (*no significant heat transfer occurs in other directions,*).

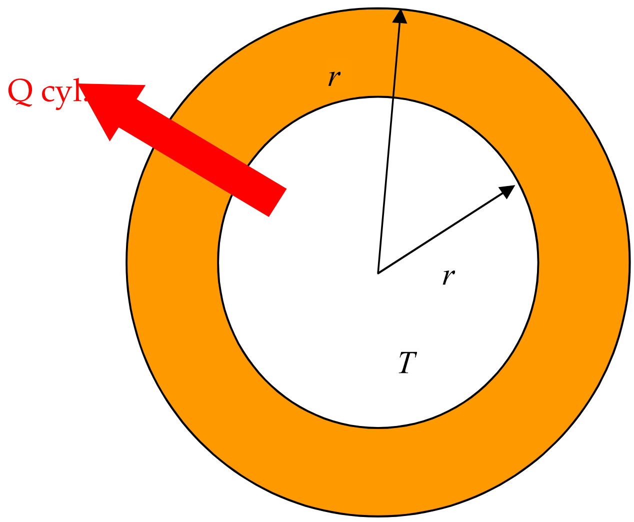

Figure 2. Steady, one-dimensional heat conduction from the furnace working zone to the outer insulation.

Therefore, the heat transfer can be modeled as steady-state and one-dimensional, and the temperature of the pipe will depend only on the radial direction, T = T (r)., also ΔT is defined as T(r1)-T(r2).

Since, there is no heat generation in the layer and thermal conductivity is constant, the Fourier law becomes:

$$Q_{\text{conduction}} = -kA\frac{dT}{dr} \quad \text{W} \tag{7}$$

Where $A = 2\pi r$L

After integration:

$$\int_{r1}^{r2} \frac{Q\ cond, cyl}{A} dr \tag{8}$$

$$= \qquad -\int_{r1}^{r2} k\ dT \tag{9}$$

Since $A = 2\pi r$;
Equation 9 may be written as;

$$Q_{\text{cond,cyl}} = 2\pi r k \text{L}\ \frac{\Delta T}{\ln {}^{r2}/_{r1}} \tag{10}$$

$$Q_{\text{cond.,cyl}} = \ 2\pi k \text{L}\ \frac{\Delta T}{\ln {}^{r2}/_{r1}} \tag{11}$$

$$Q_{\text{cyl.}} = \ \frac{\Delta T}{Rcyl} \tag{12}$$

Hence ;

$$\text{R}_{\text{cyl.}} = \frac{\ln\ {}^{r2}/_{r1}}{2\pi k L} \tag{13}$$

where Rcyl. is the conduction resistance of the cylinder layer.

Experimental Data

The furnace was tested for existing insulation of 15 mm thickness at a temperature of 1000 ° C. The results of tests are tabulated and presented in Table below. The temperatures obtained after achieving steady state conditions were;

i. Inside hot zone: 1000 ° C (T_1)

ii. Outside insulation: 718 ° C (T_2)

The multiple tests were conducted at same parameters of temperature and vacuum. The modelling of furnace was then performed to predict the numerical method accuracy. The furnace was heated at a rate of 20 ° C from room temperature to 1000 ° C after achieving the maximum vacuum in the range of 10 -4 mbar. The tests can be performed with same conditions in any furnace which is working in vacuum and has a configuration as mentioned in the manuscript. The procedures can be applied to other furnaces also if they have the same working conditions.

Sr. No	Time (min.)	Temperature inside hot zone ° C	Temperature outside insulation ° C
1	5	1000	695
2	10	1000	701
3	15	1000	705
4	20	1001	706
5	25	1002	719
6	30	1000	720
7	35	1000	721
8	40	1000	722
9	45	1000	721
10	50	1000	720
11	55	1000	720
12	60	1000	718
13	65	1000	718
14	70	1000	718
15	75	1000	718
16	80	1000	718
17	85	1000	718
18	90	1000	718

Same type of experiments were performed for the new modified furnace after increasing thickness of insulation.

Sr. No.	Time	Temperature (°C) Hot Zone	Temperature (°C) Outside Insulation
1	5	1000	445
2	10	1000	448
3	15	1000	448
4	20	1001	450
5	25	1002	452
6	30	1000	453
7	35	1000	458
8	**40**	1000	463
9	**45**	1000	468
10	50	1000	468
11	55	1000	468
12	60	1000	468
13	65	1000	468

14	70	1000	468
15	75	1000	468
16	80	1000	468
17	85	1000	468
18	90	1000	468