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6.14 Energy-efficient kiln walls

The energy cost of one firing cycle of a large pottery kiln (Figure 6.25) is considerable. Part is the cost of the energy that is lost by conduction through the kiln walls; it is reduced by choosing a wall material with a low conductivity, and by making the wall thick. The rest is the cost of the energy used to raise the kiln to its operating temperature; it is reduced by choosing a wall material with a low heat capacity, and by making the wall thin. Is there a material index that captures these apparently conflicting design goals? And if so, what is a good choice of material for kiln walls? The choice is based on the requirements of Table 6.25.

The model. When a kiln is fired, the internal temperature rises quickly from ambient, T_o, to the operating temperature, T_i, where it is held for the firing time t. The energy consumed in the firing time has, as we have said, two contributions. The first is the heat conducted out: at steady state the heat loss by

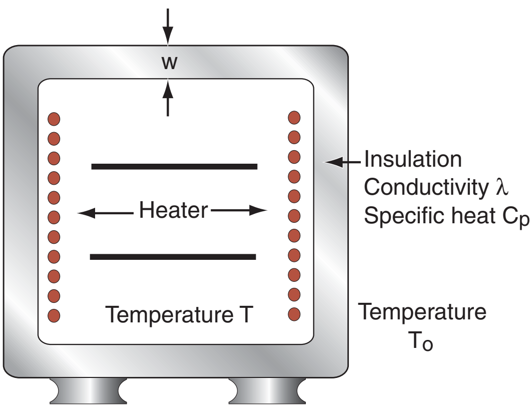

Figure 6.25 A kiln. On firing, the kiln wall is first heated to the operating temperature, then held at this temperature. A linear gradient is then expected through the kiln wall.

Table 6.25 Design requirements for kiln walls

Function	Thermal insulation for kiln (cyclic heating and cooling)
Constraints	• Maximum operating temperature 1000°C • Possible limit on kiln-wall thickness for space reasons
Objective	Minimize energy consumed in firing cycle
Free variables	• Kiln wall thickness, *w* • Choice of material

conduction, Q_1, per unit area, is given by the first law of heat flow. If held for time t it is

$$Q_1 = -\lambda \frac{dT}{dx} t = \lambda \frac{(T_i - T_o)}{w} t \tag{6.53}$$

Here λ is the thermal conductivity, dT/dx is the temperature gradient and w is the insulation wall-thickness. The second contribution is the heat absorbed by the kiln wall in raising it to T_i, and this can be considerable. Per unit area, it is

$$Q_2 = C_p \rho w \left(\frac{T_i - T_o}{2} \right) \tag{6.54}$$

where C_p is the specific heat of the wall material and ρ is its density. The total energy consumed per unit area is the sum of these two:

$$Q = Q_1 + Q_2 = \frac{\lambda (T_i + T_o) t}{w} + \frac{C_p \rho w (T_i - T_o)}{2} \tag{6.55}$$

A wall that is too thin loses much energy by conduction, but absorbs little energy in heating the wall itself. One that is too thick does the opposite. There is an optimum thickness, which we find by differentiating equation (6.54) with respect to wall thickness w and equating the result to zero, giving:

$$w = \left(\frac{2 \lambda t}{C_p \rho} \right)^{1/2} = (2at)^{1/2} \tag{6.56}$$

where $a = \lambda / \rho C_p$ is the thermal diffusivity. The quantity $(2at)^{1/2}$ has dimensions of length and is a measure of the distance heat can diffuse in time t. Equation (6.56) says that the most energy-efficient kiln wall is one that only starts to get really hot on the outside as the firing cycle approaches completion. Substituting equation (6.55) back into equation (6.55) to eliminate w gives:

$$Q = (T_i - T_o)(2t)^{1/2} (\lambda C_p \rho)^{1/2}$$

Q is minimized by choosing a material with a low value of the quantity $(\lambda C_p \rho)^{1/2}$, that is, by maximizing

$$M = (\lambda C_p \rho)^{-1/2} = \frac{a^{1/2}}{\lambda} \tag{6.57}$$

By eliminating the wall thickness w we have lost track of it. It could, for some materials, be excessively large. Before accepting a candidate material we must check, by evaluating equation (6.56) how thick the wall made from it will be.

The selection. Figure 6.26 shows the $\lambda - a$ chart with a selection line corresponding to $M = a^{1/2}/\lambda$ plotted on it. Polymer foams, cork and solid polymers are good, but only if the internal temperature is less than 150°C. Real kilns operate near 1000°C requiring materials with a maximum service temperature above this value. The figure suggests brick (Table 6.26), but

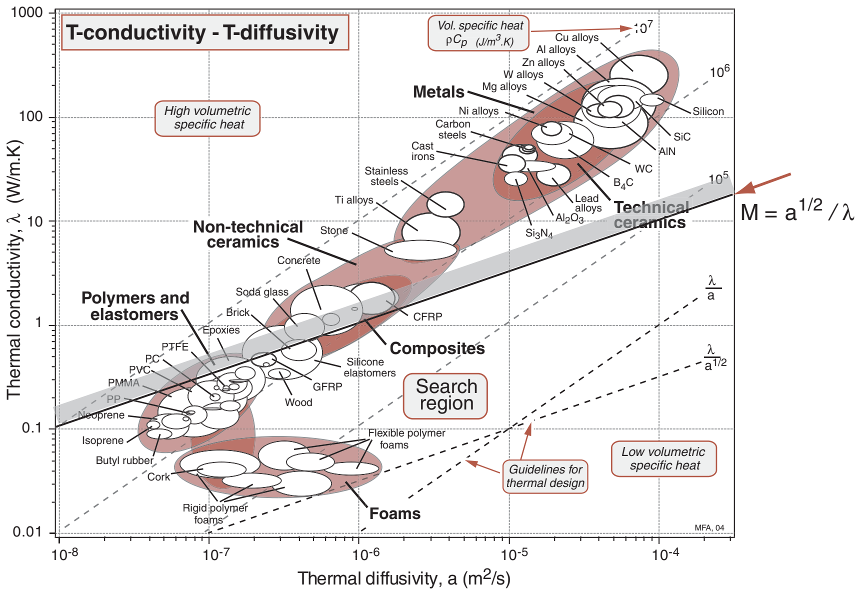

Figure 6.26 Materials for kiln walls. Low density, porous or foam-like ceramics are the best choice.

Table 6.26 Materials for energy-efficient kilns

Material	$M = a^{1/2}/\lambda$ ($m^2K/W.s^{1/2}$)	Thickness w (mm)	Comment
Brick	10^{-3}	90	The obvious choice: the lower the density, the better the performance. Special refractory bricks have values of M as high as 3×10^{-3}
Concrete	5×10^{-4}	110	High-temperature concrete can withstand temperatures up to 1000°C
Woods	2×10^{-3}	60	The boiler of Stevenson's "Rocket" steam engine was insulated with wood
Solid elastomers and solid polymers	2×10^{-3}–3×10^{-3} 2×10^{-3}	50	Good values of material index. Useful if the wall must be very thin. Limited to temperatures below 150°C
Polymer foam, cork	$3 \times 10^{-3} = 3 \times 10^{-2}$	50–100	The highest value of M—hence their use in house insulation. Limited to temperatures below 150°C

here the limitation of the hard-copy charts becomes apparent: there is not enough room to show specialized materials such as refractory bricks and concretes. The limitation is overcome by the computer-based methods mentioned in Chapter 5, allowing a search over 3000 rather than just 68 materials.

Having chosen a material, the acceptable wall thickness is calculated from equation (6.55). It is listed, for a firing time of 3 h (approximately 10^4 s) in Table 6.26.

Postscript. It is not generally appreciated that, in an efficiently-designed kiln, as much energy goes in heating up the kiln itself as is lost by thermal conduction to the outside environment. It is a mistake to make kiln walls too thick; a little is saved in reduced conduction-loss, but more is lost in the greater heat capacity of the kiln itself.

That, too, is the reason that foams are good: they have a low thermal conductivity *and* a low heat capacity. Centrally heated houses in which the heat is turned off at night suffer a cycle like that of the kiln. Here (because T_i is lower) the best choice is a polymeric foam, cork, or fiberglass (which has thermal properties like those of foams). But as this case study shows — turning the heat off at night does not save you as much as you think, because you have to supply the heat capacity of the walls in the morning.

Further reading

Holman, J.P. (1981) *Heat Transfer*, 5th edition, McGraw-Hill, New York, USA.

Related case studies

6.13 Insulation for short-term isothermal containers
6.15 Materials for passive solar heating

6.15 Materials for passive solar heating

There are a number of schemes for capturing solar energy for home heating: solar cells, liquid filled heat exchangers, and solid heat reservoirs. The simplest of these is the heat-storing wall: a thick wall, the outer surface of which is heated by exposure to direct sunshine during the day, and from which heat is extracted at night by blowing air over its inner surface (Figure 6.27). An essential of such a scheme is that the time-constant for heat flow through the wall be about 12 h; then the wall first warms on the inner surface roughly 12 h after the sun first warms the outer one, giving out at night what it took in during the day. We will suppose that, for architectural reasons, the wall must not be more than $\frac{1}{2}$ m thick. What materials maximize the thermal energy captured by the wall while retaining a heat-diffusion time of up to 12 h? Table 6.27 summarizes the requirements.