Design of transfer-limited catalytic incinerators

When mass transfer of reactants is the limiting step in a catalytic-combustion reaction, the design procedure is simplified to a number-of-transfer-units method.

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☐ The reaction of two fluids over a solid catalyst takes place in two steps: transport of reactants to the catalyst surface, and reaction at the surface. At steady state, of course, the rate of mass transfer and the rate of reaction are the same. Yet the rate may be limited by either of the two steps.

Fig. 1 shows two possible concentration profiles for a reactant over a catalyst surface. When reaction is the rate-limiting step, the surface concentration is nearly equal to the bulk concentration. When mass transfer limits the rate, the surface concentration is nearly zero. In the latter case, we can estimate the reaction rate by estimating the mass-transfer rate.

For a channel in a catalytic reactor, as shown in Fig. 2, we can express the mass-transfer rate of reactant A as a function of x:

$$\frac{d[A]}{dx} = -\frac{ak_m[A]}{v}$$

where the driving force is equal to the bulk concentration because the concentration at the surface is approximately zero. Integrating from 0 to x yields:

$$[A]_x = [A]_0 e^{-ak_m x/v}$$

When $x = v/k_m a$, $[A]_x = [A]_0 e^{-1}$. We can call $v/k_m a$ the length of a mass-transfer unit:

$$L_m = \frac{v}{k_m a}$$

For a given reactor of length L, we can calculate the number of transfer units and $[A]$ at the reactor outlet:

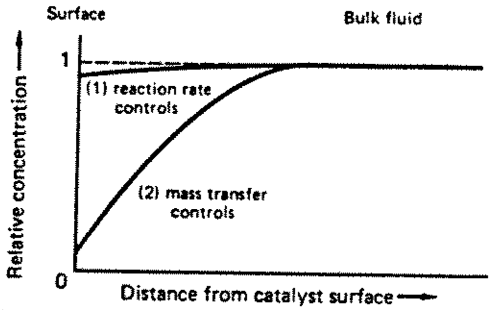
$$N = L/L_m \qquad [A] = [A]_0 e^{-N}$$

Turbulent flow

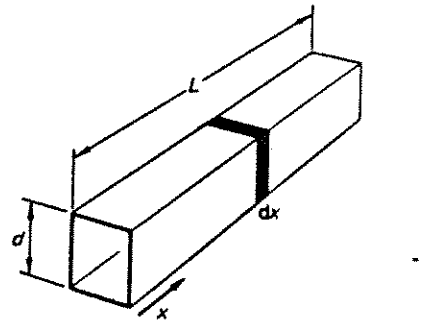
When the Reynolds number for flow in the reactor channels is greater than 2,000, the flow is considered turbulent. We can use the Reynolds analogy, which assumes that all transfer is caused by turbulent eddies, for a first estimate of the mass-transfer rate. In this case:

$$\frac{\text{rate of mass transfer}}{\text{mass driving force}} = \frac{\text{rate of momentum transfer}}{\text{momentum driving force}}$$

$$\frac{d[A]}{[A]} = \frac{-2g_c dP}{\rho v^2}$$



Concentration profiles for a reactant near catalyst surface Fig. 1

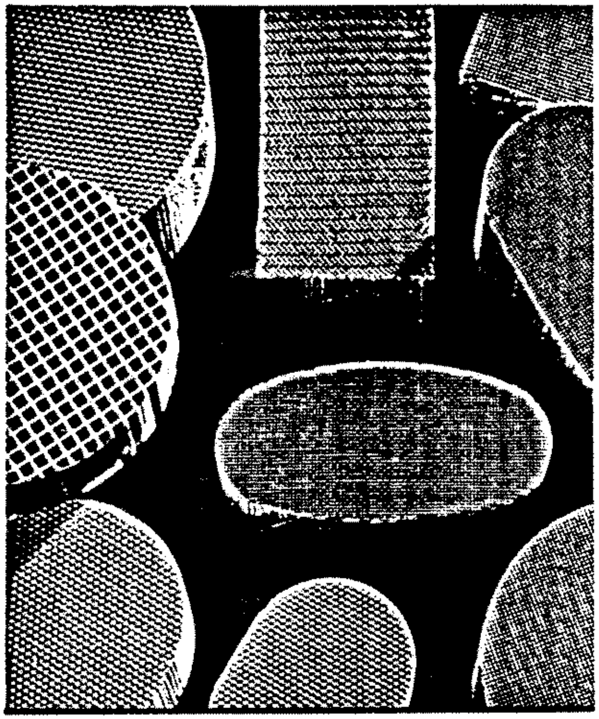


One channel of a honeycomb catalyst support Fig. 2

Introducing the mass-transfer coefficient and the friction factor converts this expression to:

$$\frac{v}{k_m a} = \frac{2}{fa} \qquad L_m = \frac{2}{fa}$$

Thus, the Fanning friction factor yields L_m directly when the Reynolds analogy holds.


Courtesy of Corning Glass Works

Samples of honeycomb-type catalyst supports Fig. 3

In the usual case, when diffusional transfer is not completely negligible, Colburn's analogy corrects for diffusional effects:

$$\frac{v}{k_m a}(Sc)^{-2/3} = \frac{2}{fa} \qquad L_m = \frac{2}{fa}(Sc)^{2/3}$$

Catalytic combustion

Catalysts are used to speed up the reactions between oxygen and organic compounds for a variety of purposes. The most common example of catalytic combustion is the oxidation of unburned hydrocarbons to water vapor and carbon dioxide in an automobile's catalytic converter. By speeding up the oxidation reaction, the precious-metal catalyst ignites the hydrocarbons below their normal ignition temperature. Catalytic incinerators that are used for fume abatement perform a similar function. For example, they can be used to control emissions of industrial solvents that cannot be vented. In the food industry, exhausts from frying and roasting operations can be incinerated to destroy objectionable odors. Table I shows several other examples of catalytic incineration. Fig. 3 shows several types of extruded catalyst supports. Though smaller holes provide greater surface area, larger holes are used when entrained particles could cause plugging.

Catalytic combustors that burn fuel upstream from gas turbines are currently being developed. Here, the advantages of catalytic combustion are threefold: less NO_x production because the combustion temperature is lower; less emission of unburned hydrocabons and carbon monoxide; greater heat release per unit volume. A recent development that improves heat release is the graded-cell support, in which hole size decreases in the direction of flow.

Examples of industrial applications for catalytic incineration [*1*] **Table I**

Industry	Flue-gas components	Incinerator inlet temperature (F)	Gas concentration (ppm) Inlet	Gas concentration (ppm) Outlet
Rhotogravure printing	Butyl acetate Ethyl acetate Isopropanol *n*-Hexane Toluene	500-800	300-1,000	7-10
Magnetic printing	MEK MIBK Toluene	500-800	1,200-2,500	8-10
Metal printing	Butanol MIBK Toluene Xylene	500-800	500-1,500	7-10
Synthetic resins	Acetone Formalin Methanol Phenol Toluene	400-600	1,200-1,500	1-20

Example data and results **Table II**

	Holes/in^2 in catalyst support		
	200	300	400
Open area, %	72	65	77
Effective hole dia., in. (d)	0.059	0.046	0.044
Velocity through holes, ft/s (v = 20/open area)	27.7	30.8	26.0
Reynolds number (Re)	153	133	107
Length of transfer unit, in. ($L_m = vd^2/17.6D$)	0.80	0.54	0.42
Length of reactor for 99% conversion, in. ($L = 4.6L_m$)	3.7	2.5	1.9
Pressure drop, in. of water	1.8	2.0	1.5

Thus, L_m for turbulent flow depends only on the friction factor—which is easy to measure—and on the Schmidt number.

Laminar flow

When the flow is laminar, all of the transfer is diffusional, and not coupled to the friction factor. We can derive the mass-transfer coefficient directly from the Nusselt number and the diffusion coefficient [2]: $k_m = Nu_m D/d$. For laminar flow, Nu_m depends only on the shape of the channel: 4.4 for circular channels, 4.1 for parallel plates, and between those two values for other shapes. In a circular channel:

$$L_m = \frac{v}{k_m a} = \frac{vd^2}{4Nu_m D} = \frac{vd^2}{17.6D}$$

Because the diffusion coefficient does not depend on the flow parameters, this relationship is very easy to use.

Example

Exhaust air from a baking oven in an enamel-coating process contains 1,000 ppm methyl ethyl ketone (MEK). The exhaust velocity is 20 ft/s, temperature is 1,000°F, and the diffusion coefficient of MEK in air is 0.00055 ft^2/s at this temperature. We have a choice of three square-holed catalyst supports—200, 300 and 400 holes/in^2—coated with a catalyst that reduces the ignition temperature of MEK to 750°F. If local air-quality ordinances demand a maximum of 10 ppm MEK in the exhaust, what length of each type do we need to reduce MEK emissions to the permissible level?

Because the exhaust temperature is above the catalytic ignition temperature, we can assume that the reaction is mass-transfer-controlled. The 10-ppm outlet concentration is 1% of the inlet concentration. Thus:

$$e^{-N} = 0.01 \qquad N = 4.6$$

Using the manufacturer's data on hole size and open area, we can calculate v and Re for flow through the holes in each type of support, as shown in Table 2. Because all of the Re values are well below 2,000, we know that the flow is laminar. We can thus use the laminar-flow equations to calculate L_m and the required reactor length ($L = NL_m$) for each type of support. If pressure drop is important, we can use Re to estimate the friction factor for laminar flow: $f = 14/Re$ for square channels ($16/Re$ in circular channels). By definition:

$$\Delta P = \frac{2fLv^2\rho}{g_c d}$$

Table 2 shows calculated reactor lengths and pressure drops for each type of support.

In this example, we did not need f to calculate L_m. If the flow had been turbulent, we could have measured pressure drops in samples of the three supports at Re values near the design values, and derived f directly from these data.

In practice, the calculated length should be considered a minimum effective length for achieving the desired conversion. Doubling the calculated length will provide an adequate safety factor in most cases; but a greater safety factor may be needed if the exhaust gases contain dust or poisons that could blind the catalyst.

Mark A. Lipowicz, Editor

Nomenclature

a	Surface area per unit volume of reactor, (length)$^{-1}$
d	Effective diameter of a channel ($d = 4/a$), (length)
D	Diffusion coefficient, (length)^2/(time)
f	Fanning friction factor
g_c	Gravitational constant, (mass)(length)/(force)(time)^2
k_m	Mass-transfer coefficient, (length)/(time)
L	Length of reactor channel
L_m	Length of a mass-transfer unit
N	Number of transfer units
v	Bulk velocity of fluid, (length)/(time)
ρ	Density of fluid, (mass)/(length)^3
μ	Viscosity of fluid, (mass)/(length) (time)
Nu_m	Nusselt number for mass transfer ($Nu_m = k_m d/D$)
Re	Reynolds number ($Re = vd\rho/\mu$)
Sc	Schmidt number ($Sc = \mu/\rho D$)

References

1. Ishihara, Y., and Fukuzawa, H., Overview of CRIEPI Catalytic Combustion Research Program, *Proceedings: Third Workshop on Catalytic Combustion*, EPA Report 600/7-79-038, U.S. Dept. of Commerce, 1979.
2. Holman, J. P., "Heat Transfer," 4th ed., McGraw-Hill, New York, 1976.

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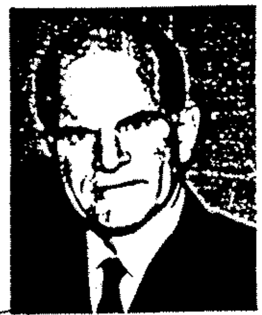

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