Activated Carbon Process for Liquids

A technique for analyzing processes using activated carbon to adsorb impurities from liquids is useful for optimizing process design, and for predicting the effect of changes in operating conditions.

Adsorption on granular activated carbon finds growing use as an effective and economical process for purifying liquids by separating low concentrations of absorbable molecules from liquids. Examples of some large-volume applications of this process are the decolorization of sugar solutions, removal of taste and odor from potable water, and the removal of dissolved organics from industrial and municipal waste streams.

In these applications, the liquid is typically passed through a static (non-fluidized) bed of the granular carbon until the adsorptive capacity of the carbon is so exhausted that the treated liquid no longer meets the purity requirement. At that time, all or part of the carbon is replaced with fresh carbon, and the spent carbon discarded or reactivated for reuse. This article presents a graphical method, which permits analysis of the two primary process variables in these adsorption processes: the volume of carbon used, and the frequency of replacement.

Unlike ion exchange and some other liquid-solids reactions, granular carbon processes are characterized by slow rates and long periods between actions. The liquid flowing through an adsorber may be in contact with the carbon for a few minutes, such as when removing the taste from water, or for several hours, as in the case of decolorizing sugar solutions. The granular carbon bed life may extend from a few days, for sugar solutions, to several years for taste removal.

These time spans make controlled testing and rigorous analysis of the process performance difficult, if not impossible. Precise test data are frequently unobtainable with any reasonable effort. In many applications, such as removal of dissolved organics from wastewater, filtration, and biological processes may also be occurring in the carbon bed. Therefore, the process design of granular carbon adsorption systems requires a thorough understanding of the basic principles involved, plus a great deal of judgment based on experience in similar applications.

Process Variables

Granular activated carbon systems generally consist of two main parts: the adsorption section and the reactivation section. Figure 1 shows a simplified flow sheet of a typical system.

The adsorber section generally consists of steel or concrete vessels, which hold the carbon bed while the liquid is passed through. These may be under-pressure or open-gravity type. Liquid flow may be upward or downward through the bed. The removal of carbon may be done essentially continuously in a countercurrent moving bed system, or it may be done batch-wise by removal of the entire bed from a single adsorber vessel.

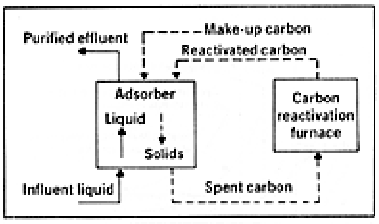

Figure 1.
Simplified flowsheet of
granular activated carbon system for liquids.

The second section of this typical system consists of a rotary kiln or multiple-hearth type furnace for reactivation of the carbon. In these, the carbon granules are returned to near-virgin adsorptive capacity. In one complete cycle of adsorption and reactivation, about 5% of the carbon is destroyed or lost in this process and must be replaced.

In these systems, the capital and operating costs are a function primarily of two variables:

1. The Carbon Exhaustion Rate

Sometimes referred to as the "burn rate" or "carbon dosage." This is usually expressed as pounds of carbon reactivated per volume of liquid.

2. Superficial Liquid Retention Time

This variable is the time that the liquid would take to fill the volume of the carbon bed and is a direct function of liquid flow rate and carbon volume.

For a given system, in which the liquid flow rate, impurity concentrations, and carbon characteristics are fixed, the costs are dependent almost entirely upon the above two primary variables. The total capital cost is established principally by the volume of the carbon beds and, usually to a lesser extent, by the size of the reactivation furnace. The operating costs are determined primarily by the carbon exhaustion rate since the largest variable is usually the cost of the make-up carbon.

The relationship between these variables can be established by tests and plotted, as shown in Figure 2. For a given system to achieve a given performance, there is a single line relating these two variables called the "operating line." As shown below, the operating line information can be used to optimize the basic design to achieve the lowest boost or other objectives.

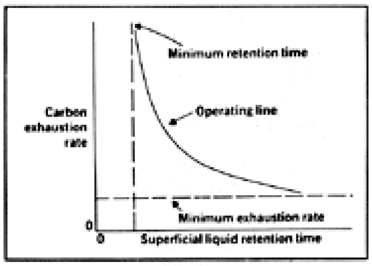

Figure 2. Example of an operating line plot.

The operating line approaches or reaches minimums on both axes. The minimum exhaustion rate for a given adsorption duty is that which is achieved when the exhausted carbon is in equilibrium with the influent liquid. As will be explained below, this value is obtained by experimentally determining the equilibrium adsorptive capacity isotherms. The "minimum retention time" represents the minimum volume of carbon necessary to achieve the desired effluent purity at infinitely high carbon exhaustion rates.

The operating line indicates the relationship between the two primary variables. Other process variables, of course, affect the position of the line. Figure 3 indicates the effect on the operating line of a change in the required level of effluent liquid purity.

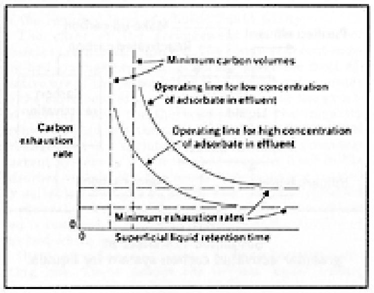

Figure 3.
Effect of effluent concentration on system operating line.

The effect of the arrangement of the adsorber vessels is shown in Figure 4. The countercurrent moving-bed arrangement will generally make the most effective use of the carbon since the liquid flow is counter to the movement of the carbon, thus giving the greatest driving force for the transport of the impurity from the liquid into the carbon. The multiple-fixed-bed arrangement is a variation on the continuous counter-current system in which the bed remains fixed in the adsorber vessels, but the vessels' positions are rotated by suitable valving. The single fixed-bed arrangement is generally the least effective since when the carbon bed is removed from service; there is still a portion of the bed, which is not exhausted.

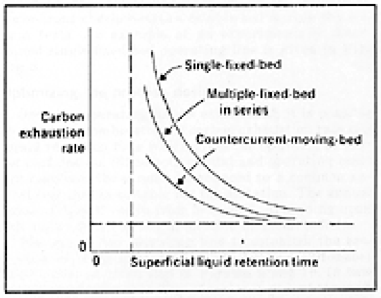

Figure 4.
Effect of adsorber column flow arrangement on system operating line.

Other secondary variables will also affect the operating line. These include the influent liquid purity, temperature, and viscosity, as well as carbon size, adsorptive capacity and other carbon characteristics. In some cases, the liquid velocity will also determine the position of the operating line.

Establishing the Operating Line

Efforts have been made over the years by Allen, Joyce, et. al., (1, 2) to relate the process variables, and to develop comprehensive methods of calculating process performance. There has been some success in this effort, and additional research is underway. However, most of today's problems must be solved using limited, and sometimes questionable, data obtained from operating plants and laboratory tests, some of which can be very time-consuming and expensive.

The minimum exhaustion rate for a given adsorption performance can be established using well-known equilibrium experiments to give a Freundlich isotherm. Figure 5 shows an example of a typical isotherm plot and the method for establishing the minimum exhaustion rate for 100% removal of the impurity. Lesser percentage removal requires lower exhaustion rates.

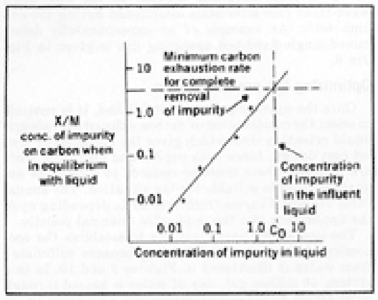

Figure 5.
Example of Freundlich isotherm for activated carbon.

The operating line for the case of a "single-fixed-bed" adsorber arrangement can be established by tests involving flowing the liquid through the carbon in a series of small columns. Figure 6 shows an example of the type of data obtained when tests are run using a total of six columns. These data are frequently referred to as "breakthrough curves." Unfortunately, in practice, these tests take days or weeks to run, the influent concentration rarely is constant, and the resulting data may be badly scattered. However, the principle is illustrated and judgment must be used to make the most of the data.

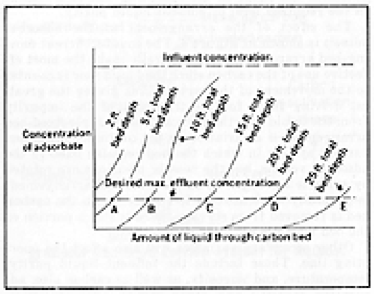

Figure 6.
Breakthrough curves from single-fixed-bed column tests.

The points on the operating line for the desired maximum effluent concentration are obtained from the column data as shown in Figure 6 and are plotted as shown in Figure 7. A variation on this technique can be used when the criteria for replacement of carbon is the average concentration of the impurity in the effluent instead of the maximum.

In theory, the countercurrent moving bed or the multiple-fixed-bed operating line can also be established from suitable laboratory tests. Even fixing one point on these lines probably would be adequate since the line should be roughly parallel to, and approach, the same limits as the single-fixed-bed line shown in Figure 7. In reality, these data are rarely obtained because of the long-time period required to achieve steady-state conditions. Consequently, the moving- bed operating line is usually established by judgment based on experience and a study of the adsorption wave-front characteristics established during the column tests. An example of an experimentally determined single-fixed-bed operating line is given in Figure 8.

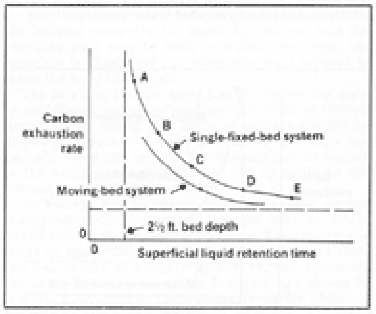

Figure 7.
Plotting the system operating lines.

Optimizing the Process Design

Once the operating line is established, it is possible to select the combination of carbon exhaustion rate and liquid retention time, which gives the optimum or lowest cost design. Since both capital and operating costs are involved, these must be reduced to a common annual cost that is suitable for the situation. The annual value of capital varies from 5- to 40%, depending upon the application and the applicable financial policies.

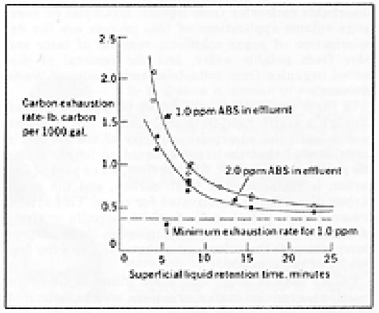

Figure 8.
Operating line for ABS in water.

The use of the operating line to establish the economics of removal of ABS (alkylbenzene sulfonate) from water is illustrated in Figures 9 and

10. In this system, 40 million gals/day of water is passed through large single-fixed-beds to reduce the ABS from 10- to 1 ppm. Figure 9 shows the capital cost of the facilities, which was based on the operating line, which was shown in Figure 8. Figure 10 indicates the annual direct operating cost and the total annual operating cost for two annual-values-of-capital. The optimum design, of course, occurs at the point of the minimum total annual costs.

In Summary

A graphical technique has been developed for analyzing the process performance of certain unit operations involving the removal of adsorbable impurities from liquids using granular activated carbon. This method gives a practical technique to optimize the process design of such systems, and to understand the interrelationship between some of the primary process variables in operating processes.

The technique is not rigorous, and complete data needed for full understanding are rarely available. Therefore, considerable judgment, based on experience, is desirable when applying this technique.

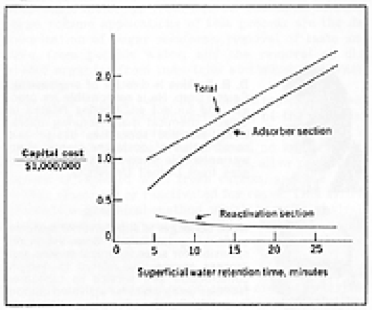

Figure 9.
Capital costs of facilities to remove ABS from water.

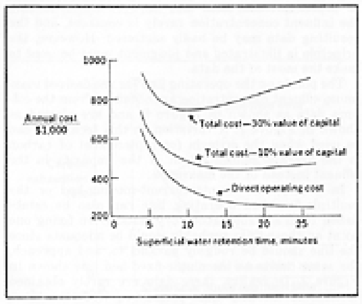

Figure 10.
Annual costs to remove ABS from water.

Literature Cited

1. Allen, J. B., T. M. Clapham. ET aI, "Use of Granular Regenerable Carbon for Treatment of Secondary Effluent-Engineering Design and Economic Analysis," Report to the U.S. Public Health Service, Dept. of Health, Education and Welfare, Contract PH 86-63-243 (October 1, 1964)

2. Allen, J. B., R. S. Joyce, and R. H. Kasch, J. Water Pollution Control Federation, 39, 217 (February 1967).