BEING DYNAMIC IN THE UNIT OPERATIONS LABORATORY

A Transient Fluidized-Bed Heat Transfer Experiment

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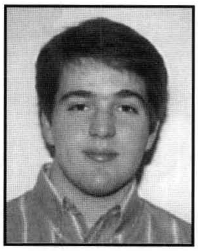
Traditionally, steady-state performance of chemical processing hardware is investigated in the unit operations laboratory, while transient behavior is reserved for the process control laboratory. But given the importance of dynamic behavior to the practice of chemical engineering, more should be done to develop students' understanding of transient process phenomena. The focus here is one of a number of unit operations experiments that form a bridge between the unit operations and process control laboratories. These experiments give students the opportunity to develop process-modeling skills and require the use of numerical methods to solve the model equations.

Specifically, a transient fluidized-bed heat transfer experiment is described that challenges students to demonstrate their understanding of fluid flow, heat transfer, and process dynamics as they apply to this particular unit operation. Students performing this experiment have previously completed introductory fluid flow and heat transfer courses and are concurrently taking courses in unit operations and process control. Thus, they are well-prepared for the experiment, and limited direct instruction is required. The students are expected to search the literature for pertinent information about fluidized beds and their operation, to formulate a mathematical model and experimental plan, and then to report their results. This fluidized-bed experiment also has the additional benefit of exposing students to particle technology, an area that is often overlooked in chemical engineering curricula.[1,2]

THE HARDWARE AND EXPERIMENT

The experiment is performed in a commercial fluidized-bed experimental apparatus (P. A. Hilton Ltd. Fluidisation and Fluid Bed Heat Transfer Unit H692; current price of $14,136). The hardware is durable, having provided years of reliable experimentation with limited maintenance requirements. Further, the small scale of the apparatus permits rapid experimentation and simplification of the process heat transfer model. Although it is not always desirable to eliminate real-world complications in the unit operations laboratory, in this instance it allows the students to focus on the primary goal of developing their understanding of transient phenomena in process operations.

A schematic of the experimental apparatus is shown in Figure 1. The bed chamber is constructed of thick glass and has an internal diameter of 0.105 m and a length of 0.220 m. The bed solid is fused alumina particles with an average particle size of 177 microns. The settled bed height is 0.067 m. Air is used as the fluidizing medium, with the flow rate being measured by either a rotameter or an orifice meter. The air is introduced through a distributor that is designed to provide both uniform air distribution over the column cross section and



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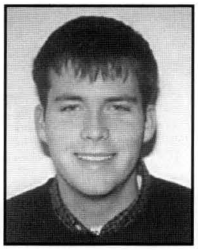

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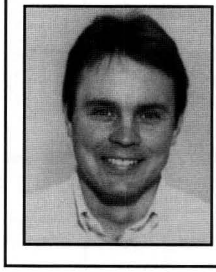

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support for the solid material in the non-fluidized state.

The bed can be heated with a resistance heater that is cylindrical in shape, has a surface area of 0.0016 m^2, and is positioned horizontally in the bed. The rate of energy input to the bed is controlled with a variable transformer and is determined by measuring the voltage drop across and the current flow through the heating element. Thermocouples with digital indicators measure the heating element, air inlet, and bed temperatures. An air-water manometer measures the pressure drop across the bed. The experimental apparatus is also equipped with safety devices to avoid dangerously high pressures and temperatures.

The initial condition of the transient experiment is a fully fluidized bed at room temperature. The transient experiment is then initiated by turning on the heating element at the desired power level (a step change stimulus). The bed temperature is then recorded as a function of time until a new steady state is approached as evidenced by a nearly constant bed temperature. The goal of the experiment is to develop a process model that can accurately predict the bed temperature as a function of time. Rice[3] has described a similar transient heat transfer experiment in which steam is used to heat a tank of water.

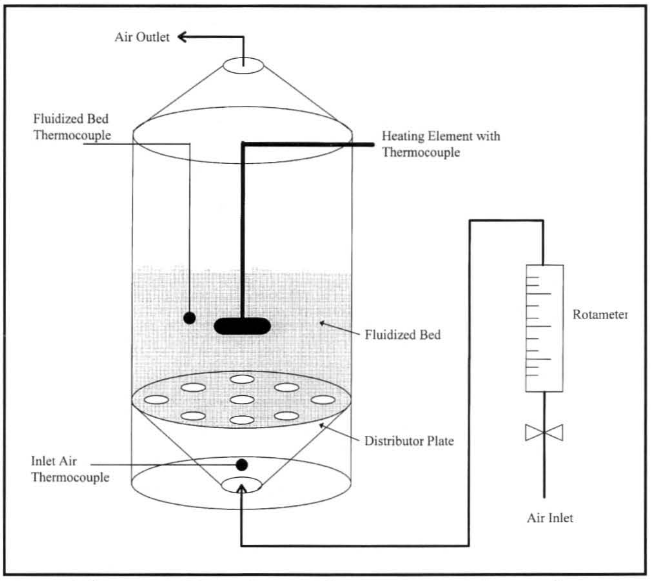

Figure 1. *Experimental apparatus schematic.*

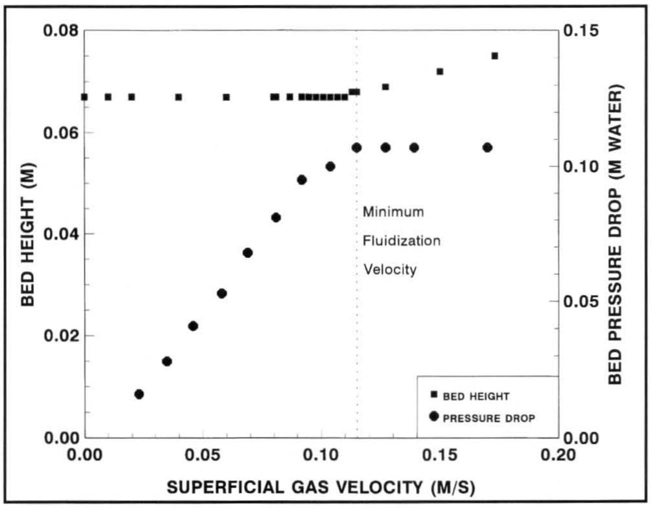

Figure 2. *Dependence of the bed height and pressure drop on the superficial gas velocity at room temperature.*

STEADY-STATE EXPERIMENTATION

In addition to the transient experiment of interest here, a number of steady-state experiments have been performed with the apparatus. As described in detail by Fee,[4] the dependence of the bed height and pressure drop on superficial gas velocity can be used to determine the minimum fluidization velocity. At superficial gas velocities below the minimum fluidization velocity, the situation is that of gas flow through a packed bed of solids. As illustrated by the experimental data of Figure 2, the bed height is independent of the superficial gas velocity in this regime, while the pressure drop increases in an approximately linear manner with increasing superficial gas velocity.[5] At minimum fluidization conditions, the upward drag force exerted on the solid particles by the flowing gas (as evidenced in the bed pressure drop) is equal to the downward force of the weight of the bed. Above the minimum fluidization velocity, the bed height increases with increasing gas velocity, while the bed pressure drop is relatively independent of gas velocity. The data of Figure 2 indicates a minimum fluidization velocity of 0.115 m/s at room temperature. Since a hysteresis effect has been observed,[5] it should be noted that the data of Figure 2 was taken as the superficial gas velocity was decreased from its maximum value (*i.e.,* the bed went from the fluidized to the packed state).

Figure 3 illustrates the dependence of the heat transfer coefficient between the submerged heating element and the bed on the superficial gas velocity (this data was obtained

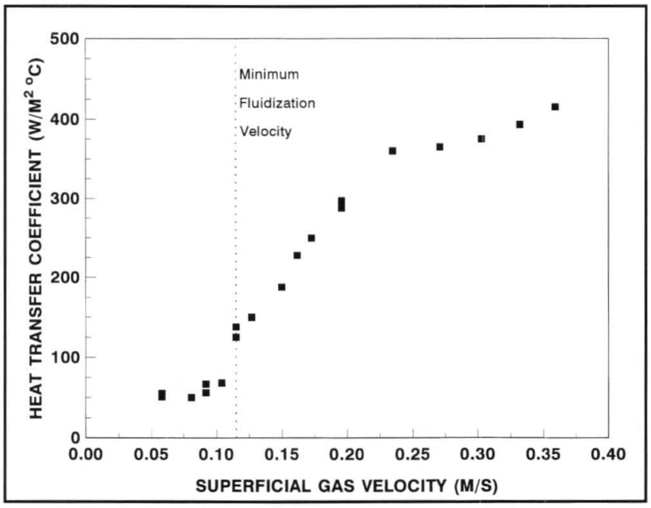

Figure 3. *Influence of superficial gas velocity on the heat transfer coefficient between the submerged heating element and the bed (based on steady-state experimentation).*

using steady-state experimentation). The data indicates that the heat transfer coefficient increases substantially upon fluidization and continually increases with increasing gas velocity. The dramatic increase in the heat transfer coefficient upon fluidization is due to the motion of the solid particles in the fluidized state.[5] Kunii and Levenspiel[6] note that a maximum heat transfer coefficient in the fluidized state often occurs at an intermediate superficial gas velocity due to large gas bubbles decreasing the particle-particle and particle-heater interactions in the bed. But this behavior is not seen in Figure 3, perhaps because the fluidizing velocities are less than that which yields the maximum heat transfer coefficient.

THE PROCESS MODEL

A mathematical model is often useful for understanding process dynamics, and developing a process model is a valuable learning experience for students. The following assumptions are used in developing a model of transient heat transfer from the submerged heating element to the fluidized bed. The bed is treated as a pseudo-homogeneous phase that has a single temperature at any point (as opposed to treating the air and solid as distinct phases). This is a reasonable assumption because the large exposed surface area of the solids in a fluidized bed leads to rapid heat transfer between the gas and solid.[7] Because of the rapid mixing that occurs in the fluidized state, the bed is assumed to be well mixed, so that the bed temperature is independent of position and is described by a single value at any time.[7] Further, because of the low thermal conductivity of the glass column, heat losses to the surroundings are taken to be negligible.

A transient energy balance of the form

$$\begin{matrix}\text{Rate of Energy}\\ \text{Accumulation}\end{matrix} = \begin{matrix}\text{Rate of Energy}\\ \text{Input}\end{matrix} - \begin{matrix}\text{Rate of Energy}\\ \text{Output}\end{matrix} \tag{1}$$

can be mathematically expressed for the bed as

$$m_b C_{pb} \frac{dT_b}{dt} = S_e - \dot{m}_a C_{pa}\left(T_b - T_{ai}\right) \tag{2}$$

The rate at which energy is added to the fluidized bed by the submerged heater is S_e, while the second term on the right-hand side of the equation represents the rate at which energy leaves the bed by heating up the fluidizing air. Note that the exiting air is assumed to have the same temperature as the bed (an assumption of the process model). Separation and integration of the model equation yields the following prediction of the bed temperature response under the conditions of the experiment (with the initial bed temperature and the inlet air temperature being equal, $T_{bo} = T_{ai}$):

$$T_b = T_{bo} + \frac{S_e}{\dot{m}_a C_{pa}}\left(1 - \exp\left[-\left(\frac{\dot{m}_a C_{pa}}{m_b C_{pb}}\right)t\right]\right) \tag{3}$$

This exponential response is typical of a first-order system.

The predicted response of the model is compared to the experimental response in Figure 4, and the conditions and model parameters of the experiment are listed in Table 1. Note that the model contains no adjustable parameters that are used to fit its prediction to the experimental response. The comparison indicates that the model does a reasonable job of predicting the experimental response. The model response at short times is more rapid than that of the experiment, however, and the experimental response is not that of a first-order system. Clearly, the process model can be improved.

REVISING THE PROCESS MODEL

The difference between the model prediction and the experimental response indicates that energy does not enter the fluidized bed as rapidly as expected. This can be explained by the presence of a thermal capacity other than the bed that absorbs some of the energy being added to the system. In this instance, the second thermal capacity is the submerged heating element itself (*i.e.,* the original process model essentially assumed that the heating element instantaneously

TABLE 1
Model Parameters and Experimental Conditions

Bed mass (m_b)	1.023 kg
Bed heat capacity (C_{pb})	761 J/kg·°C
Air mass flow rate ($\dot{m}_a$)	0.00145 kg/s
Air heat capacity (C_{pa})	1050 J/kg·°C
Initial bed temperature (T_{bo})	24°C
Inlet air temperature (T_{ai})	24°C
Rate of electrical energy dissipation (S_e)	36W

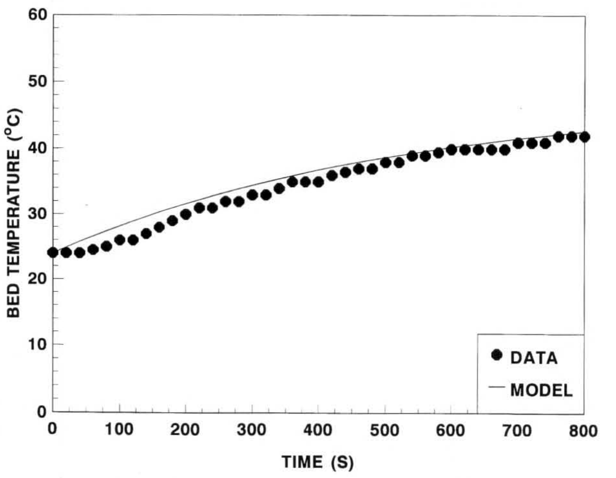

Figure 4. Comparison of the model prediction and the experimental response to a step change in power input.

reached its new steady-state temperature). The revised process model consists of simultaneous energy balances for the heating element as well as the fluidized bed.

$$m_e C_{pe} \frac{dT_e}{dt} = S_e - hA\left(T_e - T_b\right) \tag{4a}$$

$$m_b C_{pb} \frac{dT_b}{dt} = hA\left(T_e - T_b\right) - \dot{m}_a C_{pa}\left(T_b - T_{ai}\right) \tag{4b}$$

The model now reflects that the electrical energy is dissipated in, and accumulates in, the heating element and that the rate of heat transfer between the element and the bed is determined by a heat transfer coefficient. Note that the heating element has been treated in a lumped-parameter manner (*i.e.,* a single, uniform temperature is assumed). Again, the revised model does not contain any adjustable parameters because the heat transfer coefficient can be determined from steady-state experiments (refer to the results of Figure 3). The additional model parameters required by the revised process model are listed in Table 2.

The coupled model equations can be solved simultaneously to yield the heating element and bed temperatures as functions of time. Solution of the model equations is readily accomplished numerically, providing students with a good opportunity to apply their mathematical and computational skills. A fourth-order Runge-Kutta technique was used in this instance. The initial conditions for the experiment reported here are that both the bed and heating element are initially at the ambient temperature. The resulting predictions are compared to the experimental responses in Figure 5 (note that the bed and heating element temperatures are presented on separate axes). The model prediction now very accurately describes the experimentally observed bed temperature. The model prediction of the heating element temperature is less accurate, but reasonable.

TABLE 2
Additional Parameters of the Revised Model

Element mass (m_e)	0.0412 kg
Element heat capacity (C_{pe})	385 J/kg·°C
Heat transfer coefficient (h)	173 W/m^2·°C
Heating element area (A)	0.0016 m^2

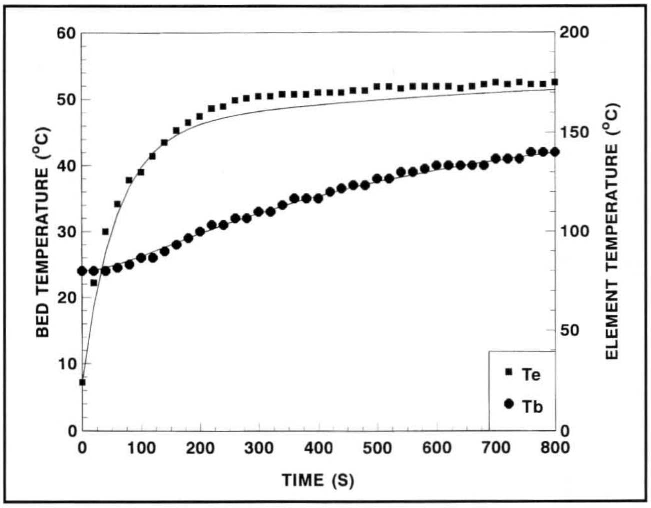

Figure 5. *Comparison of the revised model prediction and the experimental response to a step change in power input (model predictions are shown as curves).*

CONCLUDING REMARKS

The transient fluidized-bed experiment outlined here has been useful in providing students with an opportunity to study transient process phenomena in the unit operations laboratory. Because the transient experiment can be performed rapidly, students can do it after they have completed study of the steady-state behavior of the fluidized bed. The modeling and associated numerical solution of the governing model equations are additional features associated with performing transient experiments in the unit operations laboratory.

NOMENCLATURE

A	Area of the heating element
C_p	Constant pressure heat capacity (J/kg·°C)
h	Heating element to bed heat-transfer coefficient (W/m^2·°C)
m	Mass (kg)
$\dot{m}$	Mass flow rate (kg/s)
S_e	Rate of electrical energy dissipation (W)
T	Temperature (°C)
t	Time (s)

Subscripts

a	refers to the fluidizing air
b	refers to the bed
e	refers to the heating element
i	refers to inlet or feed conditions
o	refers to initial conditions

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