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Physical Modeling of the Composting Ecosystem†

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A composting physical model with an experimental chamber with a working volume of 14 × 10^3 cm^3 (0.5 ft^3) was designed to avoid exaggerated conductive heat loss resulting from, relative to field-scale piles, a disproportionately large outer surface-area-to-volume ratio. In the physical model, conductive flux (rate of heat flow through chamber surfaces) was made constant and slight through a combination of insulation and temperature control of the surrounding air. This control was based on the instantaneous conductive flux, as calculated from temperature differentials via a conductive heat flow model. An experiment was performed over a 10-day period in which control of the composting process was based on ventilative heat removal in reference to a microbially favorable temperature ceiling (temperature feedback). By using the conduction control system (surrounding air temperature controlled), 2.4% of the total heat evolved from the chamber was through conduction, whereas the remainder was through the ventilative mechanisms of the latent heat of vaporization and the sensible temperature increase of air. By comparison, with insulation alone (the conduction control system was not used) conduction accounted for 33.5% of the total heat evolved. This difference in conduction resulted in substantial behavioral differences with respect to the temperature of the composting matrix and the amount of water removed. By emphasizing the slight conduction system (2.4% of total heat flow) as being a better representative of field conditions, a comparison was made between composting system behavior in the laboratory physical model and field-scale piles described in earlier reports. Numerous behavioral patterns were qualitatively similar in the laboratory and field (e.g., temperature gradient, O_2 content, and water removal). It was concluded that field-scale composting system behavior can be simulated reasonably faithfully in the physical model.

Composting is a solid-phase process which exploits the phenomenon of microbial self-heating (14). The material being composted serves as its own matrix, permitting gas exchange, and provides its own source of nutrients, water, and an indigenous, diverse inoculum. It also serves as its own waste sink and thermal insulation. Hence, metabolically generated heat is conserved within the system, elevating its temperature.

Current interests in composting range from the traditional to the novel. Traditional, product-oriented uses of the process include the conversion of agricultural wastes to a stabilized organic soil amendment (compost) or, in an increasingly competitive industry, to a substrate for the production of edible mushrooms (mushroom compost) (5). A nontraditional, process-oriented use of composting is as a treatment technology for wastewater sludges or fractions of municipal solid waste, possibly in combination (4, 9). In this context the main goal is to stabilize and dry the waste to render it environmentally acceptable for final disposition, preferably involving some form of use of the process residue. Thus, composting is not seen primarily as a means of producing any particular product, but rather as a treatment component of an overall waste management plan. A novel area of interest is in the use of composting in the remediation of soil contaminated with relatively low levels of biodegradable hazardous wastes (7).

Composting experimentation in the field is costly and difficult to control, and it essentially excludes certain aspects of quantification. This indicates a need for a laboratory apparatus in which fieldlike behavior can be simulated. Since field practices vary widely, are rarely formalized or consistently applied, and tend to be highly empirical, the precise nature of the system to be simulated is not necessarily obvious.

This emphasizes a need to base such an apparatus on fundamental determinants of system behavior (11). Factors of overriding concern are the generation and transfer of heat, as these can have numerous effects in terms of temperature; vaporization, and water status; gaseous diffusion; and oxygen status. Significantly, the only practical means of controlling the process is through the deliberate removal of heat by means of ventilation. For these reasons we approach the general problem of composting simulation by focusing on a particular, well-characterized process control strategy based on ventilative heat management (10, 11, 13).

The idea of this strategy is to maintain a high rate of aerobic activity by removing heat ventilatively in reference to a microbially favorable temperature ceiling. Implementation is via temperature feedback control of a source of forced air. When the temperature reaches a set value, ventilation is demanded to cool the material. The demand is time variable, and the source of air must be capable of meeting the peak demand exerted during a processing cycle. A consequence of this strategy is intensive drying, because the heat is removed mostly in the form of the latent heat of vaporization of water. Heat is also removed through a sensible temperature increase of air, and this establishes a temperature gradient in the composting matrix along the airflow pathway.

Although this strategy focuses on the control of composting matrix temperature, owing to certain underlying relationships it also automatically ensures a well-oxygenated condition (8, 11). First, the consumption of oxygen through respiration results in the generation of heat, which in turn elevates the temperature. Hence, demand for cooling air in

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response to an elevated temperature is also, indirectly, a demand for oxygen resupply. Second, considerably more air is needed to remove heat than is needed to resupply the oxygen consumed in its generation. Consequently, as applied to composting, these relationships in combination render temperature feedback control an indirect form of oxygen feedback control.

This brings into relief a major problem in composting simulation, which concerns the outer surface-area-to-volume ratio. This ratio is small in field-scale piles but large in laboratory-scale masses of experimental material. Consequently, laboratory experimentation tends to involve a disproportionately large conductive heat loss. This can cause artifacts such as low peripheral temperatures, which affect a large proportion of the material in small systems. Also, since conduction detracts from evaporative cooling (the dominant ventilative heat removal mechanism), the tendency for the material to dry is decreased. As such, porosity, gas exchange rates, and oxygen status are altered at the microsite level. For faithful simulation, therefore, the conductive effect of a large surface-area-to-volume ratio must be countered.

This problem is addressed in a laboratory-scale composting physical model described here by controlling the rate of conductive heat flow from the experimental chamber independent of the ventilative heat flow. An early version of the physical model was described in detail (F. C. Miller, Ph.D. dissertation, Rutgers University, New Brunswick, N.J., 1984). An intermediate version (7) and the present one (F. C. Miller, J. A. Hogan, and M. S. Finstein, Abstr. Annu. Meet. Am. Soc. Microbiol. 1988, Q186, p. 314) have been described briefly. Specifications for fabrication of the present version and detailed descriptions of the control and monitoring software will be provided elsewhere (J. A. Hogan, M. S. thesis, Rutgers University, New Brunswick, N.J., in preparation). In the present report we describe the principal features of the physical model and provide a demonstration of conduction control and its significance.

MATERIALS AND METHODS

Overview of the composting physical model. The physical model consists of a series of integrated subsystems, as partly shown in Fig. 1. Materials of fabrication and equipment were selected not only for function but also for chemical inertness, low thermal conductivity, and dimensional stability at elevated temperatures.

Airflow regulation. Compressed air at 600 to 700 kPa (85 to 108 lb/in^2) was stepped down through a one-stage regulator to 400 kPa (60 lb/in^2). A valve downstream could be opened manually to divert air for dew point determination, and a second valve was normally open to provide air for purging gas analyzers between samples. The air destined for experimental chambers passed through an activated charcoal-impregnated filter (J-1509-25; Cole Parmer) and was then split into parallel streams, each one proceeding to a two-stage regulator (model 44-3400; Tescom Corp., Elk River, Minn.) for stepdown to 40 kPa (6 lb/in^2). Each stream then encountered a Teflon (E. I. du Pont de Nemours & Co., Inc., Wilmington, Del.)-bodied solenoid valve model V424AOFT 022; Skinner Valve, New Britain, Conn.), which served as an inlet gate. When this valve was open (its control is described below), air proceeded to a variable-area flow meter (catalog no. 10A1460NB32B; Lab Crest, Warminster Pa.). Tubing and manifolds were made of copper, galvanized or stainless steel, or Teflon.

Conditioning of inlet air. Inlet air was preconditioned to standardize it, without appreciably decreasing its heat removal capacity, and to minimize air drying. (For the important distinction between air drying and drying driven by biological heat generation, see references 13 and 18.) Air drying aggravates a tendency toward short-circuiting of air (see below).

The air coming from the flow meter was directed to a glass cylinder (height, 24 cm; diameter, 13 cm; Pyrex; Corning Glass Works, Corning, N.Y.) that was sealed at both ends with bulkheads and gaskets made of Delrin and Viton, respectively (E. I. du Pont Nemours & Co., Inc., Wilmington, Del.). A four-port manifold extended through compression fittings in the top bulkhead, with each port leading to a fritted glass air dispersion tube (12EC; Corning) immersed in distilled water. A heater (LHP400; Glo-Quartz, Mentor, Ohio) was similarly immersed and was controlled by a thermoswitch (18002-0; Fenwall, Inc., Ashland, Mass.) that extended up through the bottom bulkhead. The water was typically maintained at 22 to 24°C. The air bubbled through the water and then passed up through a 500-mm Allihn-type condenser, which was temperature controlled (e.g., 18 ± 0.2°C) with a circulating water bath (model RTE-4; Neslab Inc., Newington, N.H.). In this manner the air was conditioned and standardized to a relative humidity of 100% at a selected temperature prior to delivery to the experimental chambers.

Experimental chamber. The experimental chamber (Fig. 2) was based on a cylindrical vessel with an inside height of 45 cm and a diameter of 21 cm. Preconditioned air was introduced 1 to 2 cm above the vessel bottom through an 8-mm-inner-diameter nipple. A false floor made of perforated stainless steel (open area, 63%) was supported on legs that were 4 cm above the vessel bottom, leaving a working height of 41 cm. The nominal working volume between the false floor and the plane of the vessel rim was therefore 14×10^3 cm^3 (0.5 ft^3). The outer 3 cm of the false floor was nonperforated and was made airtight to the vessel wall with a seal made of Viton, forming a baffle. This countered a tendency of air to channel along the wall. A second baffle, similar to the first one except that the central area was entirely open, was positioned 10 cm above the first baffle. The vessel, which was cushioned with a pad, was mounted on a base made of Micarta. Threaded rods anchored to the base were used to tighten a bulkhead and gasket to the vessel rim. The vessel wall was insulated with two layers of polyurethane foam (thicknesses, 18 and 55 mm), each layer being covered with nylon fabric (Fig. 1). The bulkhead was insulated similarly. The whole assembly was wrapped in an outer fabric sleeve.

Ventilation and temperature control. The air inlet gate solenoid valve was actuated by either an electronic timer relay (part no. 0585b; Digi-Set, Inc., Liverpool, N.Y.) or a temperature controller and thermistor (model 551 and catalog no. 28-232806-304; Fenwal). The thermistor extended through the center of the bulkhead into the experimental material (Fig. 2). The timer was used to schedule base-line ventilation, and the controller-thermistor was used to provide ventilation on demand in reference to a set-point temperature (temperature feedback control). To prevent excessively frequent on-off cycling of the solenoid valve, a second timer was used as a time-delay switch to impose a minimum off time between ventilation events.

Thermocouples. Thermocouples served both temperature-monitoring and conduction-control functions. For both functions, the thermocouples were made of type T (copper-

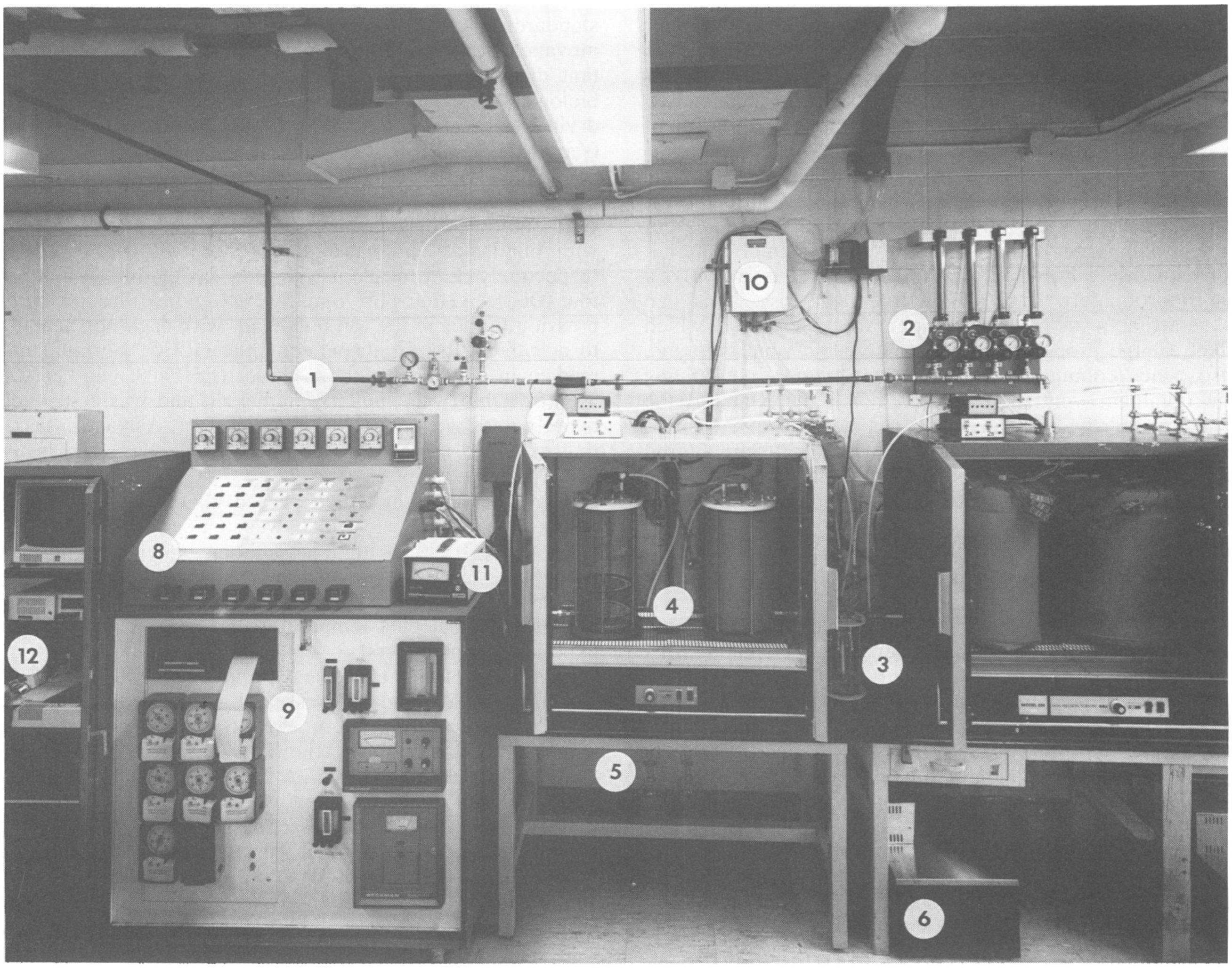

FIG. 1. Overview of the composting physical model (the electronic and control equipment is designed for three pairs of experimental chambers, but only two pairs are currently installed). 1, Air line; 2, two-stage regulators, solenoid valves (inlet gates), and flow meters; 3, air preconditioning; 4, experimental chambers (left incubator, one chamber was not insulated and one was partially insulated; right incubator, both chambers were fully insulated as in use); 5, condensate collection; 6, circulating water baths; 7, pulse rate selectors; 8, main control cabinet (includes temperature controllers and timers for actuating inlet gate solenoid valves and chart-type event recorder); 9, data logger, pneumatic multiplexer (only timers showing), and O_2 and CO_2 analyzers; 10, housing for dew point hygrometer cell; 11, dew point readout; 12, computer data collection (the computer used for conduction control is not shown).

constantan) wire and sealed with an electrical coating (Scotchkote).

Temperature monitoring. Monitoring thermocouples were read with a data logger (Digitrend 220; Doric Scientific, San Diego, Calif.), which provided a direct printout and also transmitted the data to a personal computer (PC jr; International Business Machines) for recording.

For monitoring the experimental material inside the vessel, thermocouple wire was ensheathed in stainless steel tubing to impart rigidity, while the sensing tip was left exposed. Three such probes extended through the bulkhead into the material to different depths (see legend to Fig. 2). Other thermocouples were affixed to vessel surfaces (underneath the insulation) with tape or were exposed to the surrounding air. Others were as noted in the description to exhaust gas destination control and analysis (see below).

Conduction control. The experimental chamber was housed in a modified mechanical convection-type incubator (model 6M; Precision Scientific, Chicago, Ill.). To avoid undesired warming caused by heat from the circulation fan motor, the motor compartment (separate from the incubator working space) was vented into the room mechanically.

Throughout a run the conductive flux (rate of heat flow from the chamber as a whole to the surrounding incubator air) could be maintained at a constant, preset value. This was accomplished with eight thermocouples that served a control function (these were adjacent to the monitoring ones described earlier), in conjunction with a three-segment mathematical model of conductive heat flux (see section on thermodynamic analyses below). These control thermocouples reported temperature data every 8 s to a data acquisition and control system (catalog no. WB-FAI-B16; Omega, Stamford, Conn.) for translation, via the mathematical model, into the instantaneous conductive flux. Between reports, the incubator heater was actuated, if indicated, at one of five different pulse rates, depending on any discrepancy between the actual temperature of the surrounding air and that needed to maintain the preset conductive flux. A conductive

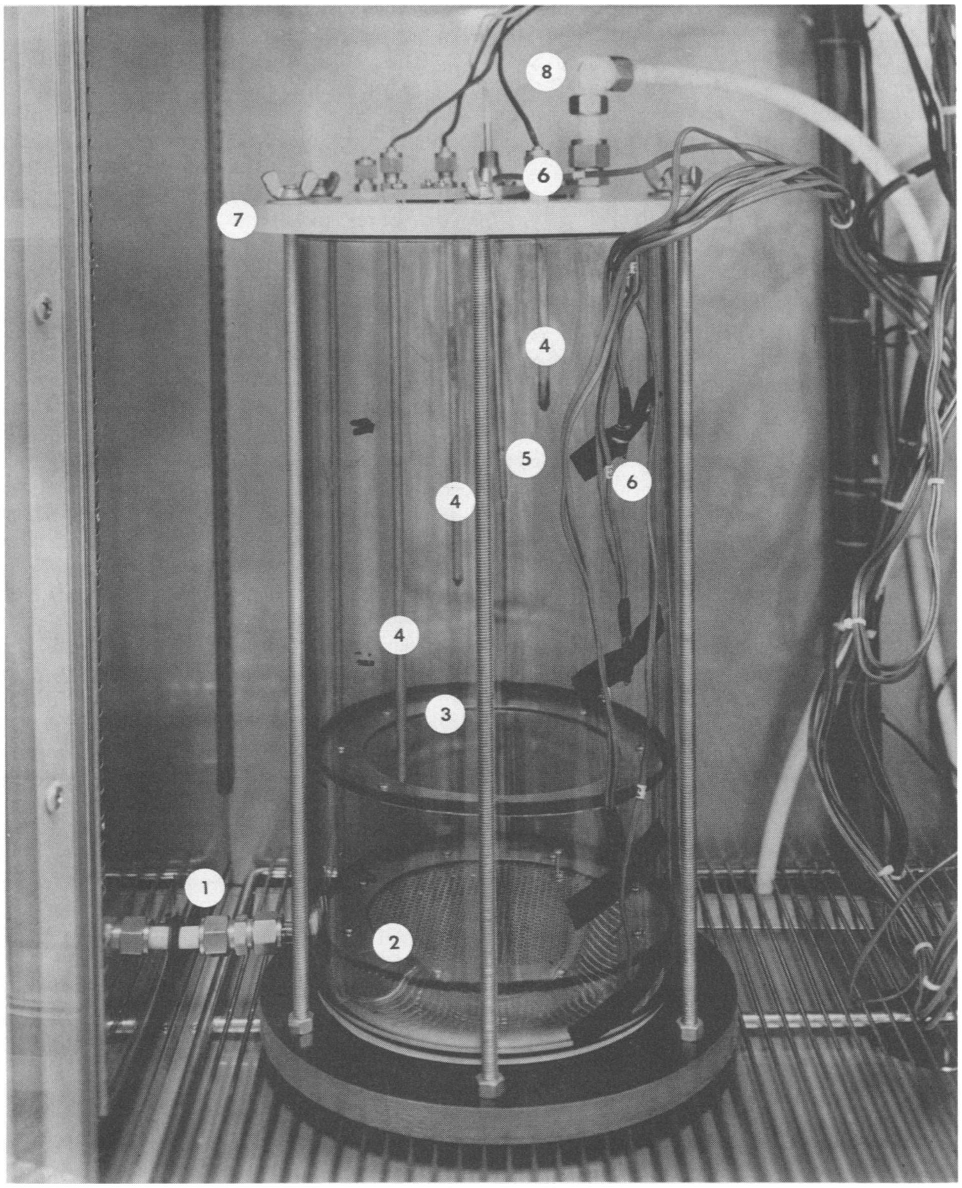

FIG. 2. Experimental chamber. 1, Tube leading preconditioned air to inlet nipple; 2, false floor and baffle; 3, upper baffle; 4, thermocouples monitoring composting material (read by data logger) at heights of 340, 215, and 90 mm above the false floor and at a radius of 60 mm from the vessel center and 45 mm from the wall at the nearest point; 5, thermistor (read by temperature controller) 265 mm above the false floor and 105 mm from the wall; 6, five pairs of thermocouples taped to chamber surfaces (one member of each pair was read by the data logger and the other was read by the conduction control system) at the following distances to the false floor level: 430, 340, 215, 90, and −25 (below false floor level) mm; 7, bulkhead; 8, outlet gas port (leads to condensate collection).

heat flux datum was recorded every 30 min as part of the thermodynamic analysis.

Occasionally, a prolonged period of demand for ventilation cooled the vessel bottom such that, to maintain the preset conductive flux, the surrounding air needed to be cooled more quickly than occurred through the usual loss of heat from the incubator to the room. In this circumstance, the surrounding air was automatically vented from the incubator through a wall-mounted fan. The instruction to vent was part of the program resident in the data acquisition and control system.

Exhaust gas destination control and analysis. Exhaust gas exited the experimental chamber via an outlet port in the bulkhead and was then directed downward through the incubator floor to two 300-mm-long condensers in series. These were surrounded by insulation in an airtight enclosure and maintained, with a second circulating water bath, at a constant temperature (typically, 1°C). The condensate was collected in a 1-liter round-bottom flask. A thermocouple was taped to the second condenser near its terminus to monitor the dew point temperature of the exiting gas. For occasional verification, this gas stream was shunted manually to a dew point hygrometer (model 880; EG&G, Waltham, Mass.). Similarly, nonpreconditioned air could be shunted to this instrument (see section on airflow regulation above). Upon exiting the condensers, the gas could be passed through activated charcoal to trap volatile compounds.

Exhaust gas was then normally vented from the building via a low-pressure duct and hood, but it could first be directed to O_2 and CO_2 analyzers (models 775 and 865, respectively; Beckman Instruments, Inc., Fullerton, Calif.) with a pneumatic multiplexer. Automatic gas sampling and analysis could be scheduled with timers, with the data recorded on a strip chart (8720A; Beckman). Between samplings, the tubing and analyzers were purged with nonpreconditioned air.

Ventilation event monitoring. Ventilation events and their durations were monitored by determining whether the inlet gate solenoid valve was open or closed. Two independent monitoring devices were used. One employed a modified computer (XL800; Atari, Sunnyvale, Calif.) and a program that queried each inlet gate solenoid valve 1,228 times per s regarding its open or shut status. An hourly digital printout recorded the proportion of the time the valve was open. The second device, a multichannel chart event recorder (Gulton Industries, East Greenwich, R.I.), recorded the individual ventilation events.

Thermodynamic analyses. Biological activity was measured, in terms of the heat evolved from the experimental chamber, by a thermodynamic analysis subdivided into ventilative and conductive components, as summarized below.

First, the amount of heat removed ventilatively was calculated based on the enthalpy (heat content) differential between the preconditioned inlet air and experimental chamber outlet gas. Standard psychrometric data were used (1). The volumetric flow rate, duration of ventilation events, dew point temperature, and temperature of the incoming air (prior to conditioning) were used to calculate the mass of dry air. The preconditioning regimen determined the inlet air temperature and relative humidity, which defined its enthalpy (heat per mass of dry air). The temperature of the outlet gas was derived based on the amount of condensate that was collected. (A correction was made for a small amount of water vapor which exited from the condensors.) This temperature derivation required that the outlet gas relative humidity be known. Based on independent lines of evidence (see below), this was considered to be 100%.

Second, the conductive heat flux from the experimental chamber to the surrounding incubator air was both preset and monitored (see conduction control section) by using a three-segment mathematical model. The different segments of the mathematical model represent the top end (bulkhead), middle (vessel wall from rim to the level of the false floor), and bottom end (vessel floor) of the physical model. The temperature of the top end was represented by the thermocouple affixed to the bulkhead, the middle by the three affixed to the vessel wall between the levels of the rim and the false floor (mean value used), and the bottom end by the one affixed to the wall below the false floor level (Fig. 2). The mathematical model was based on the thermal conductivity of the various materials used in constructing the chamber, the geometry and areas of the various surfaces, and the temperatures representing the differentials between the outer vessel surfaces (beneath the insulation) and the surrounding incubator air. Each surface temperature (or mean) was compared with that of the surrounding air at the comparable level. The thermal conductivity of each segment was distinct.

The equation used to calculate the conductive flux through the base and bulkhead, which were flat surfaces, was $q = KA(T_O - T_I)/X$, where q = conductive heat flow, A = area of conductive surface, K = thermal conductivity, X = thickness of insulation, T_O = outer temperature, and T_I = inner temperature.

The wall of the chamber had a cylindrical geometry and required a different formula: $q = 2\pi HK(T_O - T_I)/\ln(r_O/r_I)$, where H = height of the cylinder, r_O = outer radius of insulation, and r_I = inner radius of insulation.

The K value used for the polyurethane foam insulation was 9.3×10^{-5} cal/s · cm · °C. The insulating properties of the other materials of fabrication were also taken into account.

A calculation period for overall heat evolution (ventilative plus conductive) was defined by the interval between measurements of the amount of condensate, which was typically 8 or 12 h. The amount of heat evolved over an entire run was expressed based on the initial dry mass of experimental material in the chamber. Also, a time course rate expression of heat evolved from the chamber was based on the mass present at the start of each calculation period. The mass for the first period was that measured at time zero, and for the final period it was that measured at termination. The mass for the intervening periods was estimated as follows: estimated mass = preceding period mass − [(time zero mass − terminal mass) × (heat evolved over calculation period/heat evolved over entire run)].

Demonstration of the physical model. The demonstration of the physical model involved a mixture of whole and finely ground rice hulls (J. B. Hunt Co., Stuttgart, Ark.) and rice flour (local market) in a fresh weight ratio of 50:34:16 (whole hulls-ground hulls-flour). Moisture content was determined through drying at 104°C, and volatile solids content was determined through ashing in a muffle furnace (both done in triplicate). The as-received moisture content of all the components was approximately 10%. Mixing was done in a 90×10^3-cm^3 (3-ft^3) cement mixer. The moisture content was adjusted with tap water, and nutrients were added as follows, in milligrams per gram (dry weight): NH_4Cl-N, 2.5; KH_2PO_4-P, 1.6; Na_2SO_4-S, 0.5.

Two experimental chambers were filled with the mixture. The dry weight content of chamber A was 2,965 g, and that of chamber B was 2,895 g. Each chamber was placed into a separate incubator.

The experimental variable was conductive heat flow (see below). All other operational parameters were the same for both chambers, as follows: inlet air, 18 ± 0.2°C and 100% relative humidity (after preconditioning); ventilation rate, 15 liters/min; initial base-line ventilation schedule, 1 continuous min every 10 min; terminal base-line schedule, 0.5 continuous min every 10 min; temperature feedback control set point, 50°C; time delay (minimal interval between ventilation events), 1 min; outlet gas condensor temperature, 1°C; insulation, both chambers fully insulated as described above. At termination, the contents of the each vessel were thoroughly mixed prior to sampling.

RESULTS

Preliminary trials demonstrated that ordinary differential temperature control of the surrounding air, in which the temperature data were not translated into conductive flux (rate of heat flow through experimental chamber surfaces to surroundings), is not ideal for controlling conduction. In these trials the chambers were insulated as described above. Despite frequent manual resetting of the temperature differential based on ad hoc calculation of the conductive flux, it was not possible to maintain the flux at a reasonably constant level. The problem was that the conductive fluxes through the three segments of the experimental chamber, as represented by the three-segment mathematical model, were affected differently by changes in the steepness of the ventilation-induced vertical temperature gradient. This experience led to the development of the conduction control system described here. It employed the instantaneous conductive flux itself as the parameter for controlling the surrounding air temperature.

Control of conduction was demonstrated as part of a comparative study on the effects of conduction on composting system behavior. The conduction control system of experimental chamber A was used, whereas that of chamber B was not. The setting for chamber A was to maintain a constant, slight conductive flux of heat from the chamber as a whole. Chamber B, like chamber A, was insulated to decrease conduction and also to help maintain a ventilation-induced temperature gradient in the peripheral material. Since the conduction control system of chamber B was not used, its conductive flux was dependent on the temperature of the composting material, the steepness of the ventilation-induced temperature gradient, and the temperature of the surrounding air. To prevent exposure to strong drafts, chamber B was housed in one of the incubators; but to prevent any substantial accumulation of biologically generated heat in the surrounding air, its incubator doors were kept ajar. All other operational parameters were the same for both chambers.

Throughout the study period ventilative air was delivered to the experimental chambers on a base-line schedule (Fig. 3). The initial schedule was designed to maintain an oxygenated condition while avoiding excessive heat removal, to promote, as rapidly as possible, temperature ascent and engagement of feedback control. The terminal schedule (half the initial schedule) was designed to maintain a well-oxygenated condition, while avoiding excessive ventilative involvement in the temperature descent. During an intermediate period the self-heating material exerted, via temperature feedback control, a demand for additional air.

During the ascent, vertical temperature gradients (temperature increases with height), although shallow at first, became established along the airflow pathway. At the respective control thermistor positions, temperature reached the set point of 50°C and engaged feedback control at 28.5 h (chamber A) and 30.0 h (chamber B). In both chambers the engagement of feedback control moderated, arrested, or even temporarily reversed the temperature ascent. Also, the onset of feedback control greatly steepened the vertical temperature gradients. The steepest gradients observed between the levels of the lower and upper monitoring probes in the composting material were, respectively, 16 and 21°C/25 cm (vertical distance between these probes). The set point (50°C) was consistently maintained at the control thermistor position of both chambers (data not shown). In both chambers the temperature at the topmost monitoring position (above the control thermistor level) peaked at approximately 55°C.

The initial base-line schedule delivered 0.04 g of air per g of starting material per h (on a dry weight basis of expression for both air and material). With the engagement of feedback control, the demand for ventilation increased rapidly to peak values of, for chambers A and B, respectively, 0.165 and 0.155 g of air per g of material per h. The peak demands were transient, however, and sharp declines quickly set in. This led to a cessation of demand at 130 and 110 h, respectively, disengaging feedback control. Meanwhile, as noted earlier, the base-line schedule was halved. Total deliveries (demanded and base line) were 11.5 and 10.6 g of air per g of material, respectively.

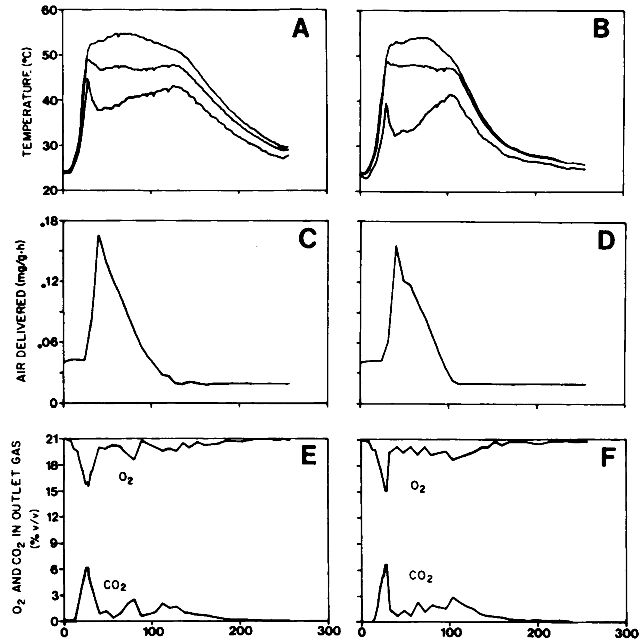

FIG. 3. Matrix temperature, air delivered, and outlet gas composition. (A, C, and E) Chamber A; (B, D, and F) chamber B. (A and B) Temperatures at heights above false floor (top to bottom curves) of 340, 215, and 90 mm, respectively. (C and D) Air delivered to the starting material, as scheduled for base-line ventilation (includes sampling events) and as demanded via temperature feedback control. (E and F) O_2 and CO_2 in outlet gas; prior to the onset of temperature feedback the gas sampling coincided with the scheduled ventilation events, and subsequently, it was random with respect to the scheduled ventilation events.

Temperature declines set in during the terminal period of base-line ventilation, and the temperature gradients became less steep. Both trends were more pronounced in chamber B. At the termination of the experiment, the temperature of the material in chamber B was close to the ambient temperature, while that in chamber A was still somewhat elevated.

Although temperatures in chamber B, as a whole, were appreciably lower, the demand for ventilation was only slightly lower. This stems from the relative positions of the monitoring and control probes. The temperature-monitoring probes (thermocouples) were positioned off center at a nearest distance to the wall of 43 mm, whereas the control probe signaling ventilation demand (thermistor) was central at a distance of 105 mm. Because of the additional conductive path length to the wall, the control probe was less affected by conduction than the monitoring probes were. This accounts for the fact that the demand for ventilation in chamber B was only slightly less than that for ventilation in chamber A, although on average its material was at a substantially lower temperature.

During the initial base-line period, outlet gas sampling was initiated manually every hour to coincide with a scheduled ventilation event, to represent the interevent low point for O_2 content and the high point for CO_2 content (Fig. 3). The trends were indicative of an intensifying community respiration. The lowest O_2 residuals (15%) and highest CO_2 elevations (approximately 6%) occurred just prior to engagement of temperature feedback control. Once feedback control

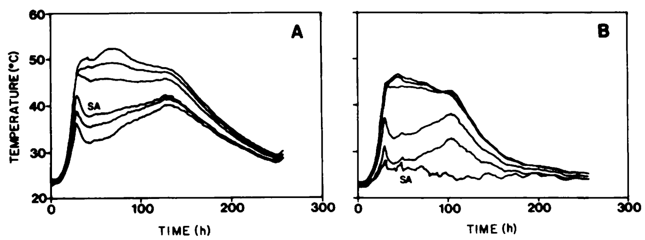

FIG. 4. Temperature at vessel surfaces underneath insulation (five positions) and exposed to surrounding air (SA). (A) chamber A; (B) chamber B. Distances to the false floor level (top to bottom curves, not including surrounding air): bulkhead, 430 mm; wall, 340, 215, 90, and −25 (below false floor level) mm. The surrounding air temperature is represented by the mean of the values at the 340-, 215-, and 90-mm levels. The abrupt, slight temperature increase just prior to termination (chamber A only) was caused by the inadvertent shutoff of the fan circulating the surrounding air.

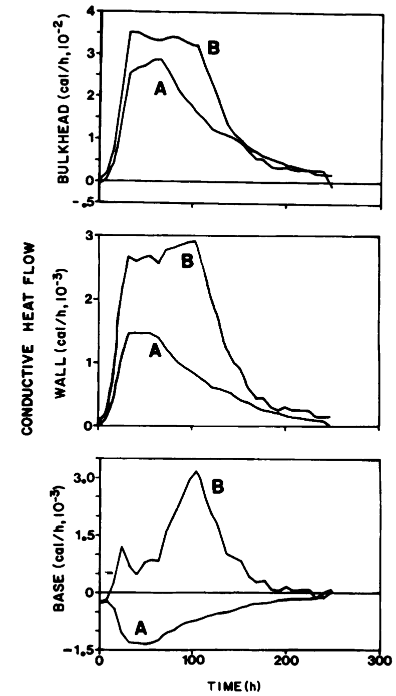

FIG. 5. Thermal conduction from different segments of the experimental chambers (1 cal = 4.184 J). Chambers A and B are as indicated.

became engaged, it was not possible to systematically sample outlet gas relative to specific ventilation events, and for the remainder of the trial (including the terminal base-line period) sampling was initiated automatically every 8 h at random with respect to events. It was nonetheless evident that feedback control promptly returned the O_2 residuals to within a few percentage points of the ambient value. As summarized earlier in this report, this reflects underlying relationships linking ventilative heat removal and O_2 consumption (8, 11). Conversely, the greater amount of air passing through the matrix swept out the CO_2 with a greater dilution.

As described above, the temperature data representing outer vessel surfaces (underneath insulation) and surrounding air (Fig. 4) were instantaneously translated via the three-segment mathematical model into estimates of the conductive heat flux (Fig. 5). In the constant conductive flux mode of operation, the individual flux values were summed and used in the control of surrounding air temperature. Chamber A was operated in this mode with a setting to maintain a slight outward flux for the chamber as a whole. Thus, the inward flow of heat through the lower part of the chamber was dynamically counterbalanced (plus a slight excess) by the outward flow through the upper part. The result was that the conductive flux for the chamber as a whole was outward, virtually constant, and slight (note the sums at any particular time; see Fig. 7).

The conduction control system of chamber B was not used. Consequently, not only was the conductive flux from each segment of the chamber time variable but the sums representing the chamber as a whole were also variable. Moreover, the conductive loss of heat was substantial.

In addition to the ventilation-induced vertical temperature gradient along the airflow pathway, there was a conduction-induced horizontal gradient within the matrix. This was manifested at paired monitoring positions representing the composting matrix and outer vessel wall, underneath the insulation, at corresponding levels (compare selected curves in Fig. 3 and 4). Over the distance spanned (43 mm of composting material and 6 mm of glass wall thickness), the horizontal temperature differentials ranged from 1 to 5°C in chamber A to 5 to 9°C in chamber B.

The temperature of the gas as it emerged from the composting matrix and passed through the outlet port was derived as described above. With a minor exception at 39 h, the outlet gas temperature of chamber A was higher than that of chamber B (Fig. 6). This reflects a greater conductive involvement in chamber B and the resultant lower overall matrix temperatures. Consequently, the outlet gas of chamber A contained more moisture, and its matrix moisture content decrease was more pronounced (terminal values, 38 versus 46%, respectively). These differences occurred despite the delivery of only slightly more air to chamber A (Fig. 3; note the comment on the location of control and monitoring probes). The net amounts of water removed from chambers A and B were, respectively, 0.78 and 0.57 g of water per g (dry weight) of starting material (water introduced in the inlet air was not included in the calculation).

Various observations were integrated into the estimate of heat flux (Fig. 7). Throughout the trial the conductive flux from chamber A was nearly constant and slight, as intended. Overall, conduction amounted to 2.4% of the total flux from this chamber; hence, nearly all of the heat was removed through ventilative mechanisms. The operational mode of chamber B did not control the conductive flux, and this varied over time in both absolute terms and relative to the ventilative heat flux. Overall, conduction accounted for 33.5% of the total heat flux from chamber B.

Although the relative contributions of ventilation and conduction to total heat flux differed substantially, the totals were similar. For chambers A and B, respectively, the total fluxes (ventilative and conductive) over the entire experimental period were 578 and 628 cal/g (dry weight) of starting material.

Materials balance calculation indicated that, for chambers A and B, respectively, 16.9 and 15.7% of the total dry solids disappeared over the course of the trial. Based on this calculation, the total heat flows can be expressed as 3,403 and 4,003 cal/g (dry weight) of material that disappeared. The production of water metabolically amounted to 0.50 and 0.53 g/g (dry weight) of material that disappeared. The initial

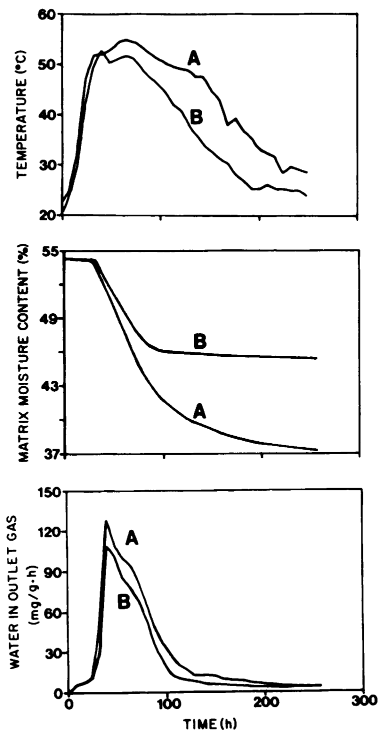

FIG. 6. Calculated temperature of outlet gas, matrix moisture content (wet weight basis of expression), and water in outlet gas (milligrams of water per gram [dry weight] of starting material per hour). Chambers A and B are as indicated. The starting and terminal moisture contents were determined, and the intervening values were derived (see text). Water was that collected as condensate every 8 h, as corrected for vapor exiting from the condensers.

volatile solids content of the experimental mixture was 81.0%, and the terminal value for both chambers was 77.9%.

Visual inspection at the termination of the experiment showed that in both chambers the underside of the bulkhead, the top few millimeters of composting material, and the vessel wall near the rim were conspicuously wet. This wetness was circumstantial evidence that the outlet gas was saturated. That a saturated condition prevailed throughout the experimental period was also indicated by the wide temperature differentials between the bulkheads and the surrounding air (Fig. 4).

A layer of material a few millimeters thick just above the false floor, where the air first entered the composting matrix, was dry. Otherwise, the bulk of the material in each chamber appeared to be uniform with respect to moisture content.

DISCUSSION

The composting physical model described here imposes certain spatial and thermodynamic boundary conditions which define, to a significant extent, the region of the field-scale system being simulated. Spatially, the experimental chamber is a cylinder with a working diameter of 0.21 m and a height of 0.41 m. In comparison, field-scale composting piles are variously shaped, extend horizontally for many meters, and are typically 2 to 3 m in height. Thermodynamically, the physical model can be operated variously to mimic various field circumstances as imposed by design or default. The spatial and thermodynamic aspects are not entirely separable.

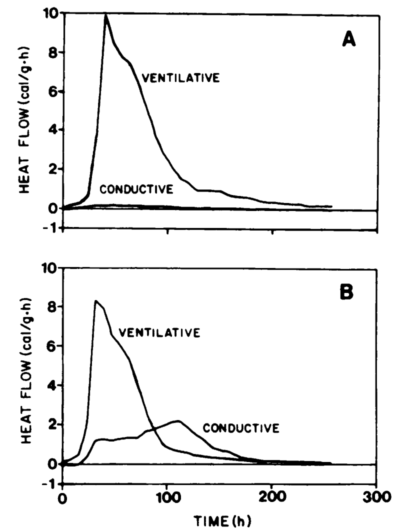

FIG. 7. Heat evolved from chambers through ventilation-associated mechanisms (latent heat of vaporization and sensible temperature increase of air) and thermal conduction (calories per gram [dry weight] of starting material per hour). (A) Chamber A; (B) chamber B.

With respect to horizontal boundary conditions, the contents of an experimental chamber can be viewed as representing an inner core of a field-scale pile. The horizontal flow of heat from the core to the surrounding material can be considered to be solely a function of conduction. Composting material is a poor thermal conductor, as indicated in tests of 64 such materials which differed with respect to bulking agent, composting history, and moisture content. All were derived from sewage sludge. Their conductivities ranged from 0.62×10^{-3} to 2.1×10^{-3} cal/s · cm · °C, with a median of 1.5×10^{-3} cal/s · cm · °C (M. Rahman, Ph.D dissertation, Rutgers University, New Brunswick, N.J., 1984). This median value is only 6.2 times greater than that of the polyurethane insulation used in the physical model (see above). Moreover, in a field-scale pile the temperatures on both sides of the spatial boundary would be similar, providing little driving force for conductive transfer. These considerations indicate that horizontal conduction from an inner core of field-scale piles is ordinarily slight.

Field data to evaluate the indication given above that internal conductive flow is ordinarily slight seem lacking. However, three studies have been reported on the flow of heat through various mechanisms from whole field-scale systems to the environment. All three systems so studied were deliberately ventilated and involved the composting of wastewater sludge. One system was an experimental batch (6), and the other two were different facilities in routine operation on a semicontinuous basis (2). The heat flows were accounted for as follows, as percentage of overall flow to the environment: conduction, 2, 4, and 11; latent heat of vaporization, 88, 86, and 76; and sensible temperature increase of air, 10, 9, and 12. (In those cases in which the sums are less than 100%, the difference represents a sensible temperature increase of the material. This did not enter into the analysis of the batch system.) Thus, the contribution of conduction is relatively small. Moreover, since conduction from a whole pile occurs at outer surfaces, much of the heat lost through this mechanism is probably generated in peripheral material. These studies thus support the idea that temperature differentials over short interior distances within field-scale piles are generally slight and that an inner core is typically little affected by horizontal conduction.

With respect to horizontal conduction in the laboratory-scale physical model, consider separately the roles of the polyurethane insulation and the conduction control system (surrounding air temperature controlled based on instantaneous conductive flux). Chamber B was only insulated, whereas chamber A was insulated and its conduction control system was used.

Insulation decreases conduction in general and, in this special case, helps maintain the ventilation-induced vertical temperature gradient in the peripheral material. Although in principle a slight conductive flux similar to that in chamber A could be approached through the use of more effective insulation, there are severe practical limitations. One method would be to fabricate an experimental chamber in the form of a vacuum flask (Dewar flask), but as applied to composting this would be technically difficult. Another method would be to increase the thickness of the insulation, but again this is limited by technical difficulties. Consider the case when chamber B is surrounded by additional polyurethane foam to a thickness of 3 m and there is a temperature differential (temperature of vessel surfaces versus that of surrounding air) of 14°C. Calculation shows that the instantaneous conductive flux, although greatly decreased, would still be 50-fold greater than that from chamber A. This counterintuitive result stems fundamentally from the difference between insulation alone and insulation plus surrounding air temperature control. Whereas the former serves only to resist heat flow, the latter substitutes for biological heat generation in material that would surround the inner core of a large pile.

Moreover, use of insulation alone, even if highly effective, leaves conduction as an uncontrolled experimental variable. This is important in that the most practical means of controlling field-scale composting piles is through deliberate ventilative heat removal (11). As such, for many experimental purposes conduction should be one of the factors that is held invariant. This necessitates use of the conduction control system.

In using the conduction control system, a range of settings can be selected to govern the magnitude of the conductive flux. In principle, the lowest setting consistent with the need to avoid overall inflow to the chamber as a whole is for a conductive flux of zero. Yet, operation too close to a zero setting could inadvertently lead to an overall inflow. To guard against this condition but still mimic an interior core experiencing little conductive loss, the setting for chamber A was for a slight outward flux. The upper available setting, to provide for a substantial, constant outward flux, depends on the maximum temperature differential between the composting material and the room.

The realized performance was that, as intended, the conductive flux from chamber A was essentially constant and slight (Fig. 7). In contrast, the flux from chamber B was variable and substantial. For a brief period at the start of the experiment, there was a small overall conductive flow into both chambers (room temperature higher than the temperature of the time zero mixture). Over the entire 10-day experimental period, conduction accounted for 2.4% of the total heat flow from chamber A and 33.5% from chamber B. The chamber A system can thus represent an interior core of a large (ordinary-size) field pile, and chamber B can represent a core of an unusually small one.

As seen when the behaviors of the two systems were compared, the effects of the conductive differential were manifested in various ways. The largest effects were on matrix temperature and moisture status. The temperatures of chamber A were generally higher, whereas the terminal moisture content in chamber A was lower (38 and 46% in chambers A and B, respectively). The amounts of water removed were, respectively, 0.78 and 0.57 g of water per g (dry weight) of starting material. Other comparative results with respect to factors susceptible to temperature effects, and hence, potentially responsive to conduction, were as follows in chambers A and B, respectively: time of engagement of temperature feedback control, 28.5 and 30.0 h; disengagement of feedback control, 130 and 110 h; peak demand for ventilation, 11.5 and 10.6 g of dry air per g (dry weight) of starting material; total heat evolved, 578 and 628 cal/g (dry weight) of starting material; proportion of total dry solids decomposed, 16.9 and 15.7%. The comparative inconsistency between heat evolved and solids decomposed cannot be explained.

Other investigators (2) have reported the conduction from a well-insulated composting experimental chamber accounted for 61.6% of the overall heat flow. The conductive flux per se was not reported.

The discussion presented above is concerned with the horizontal boundary condition. The matter of the vertical boundary condition should be addressed. Provided that temperature feedback control is used in both the laboratory and the field, two types of boundary conditions with respect to height can be imposed. In the first, which was demonstrated in both chambers in this study, the 0.4-m working height of the chamber corresponded to the full height of a field pile (perhaps 2 to 3 m). In the second type of vertical boundary condition, the 0.4-m height of the chamber corresponded to a 0.4-m segment of a field pile. The location of this segment along the vertical axis of the field pile must be specified (see below).

With respect to the first type of vertical boundary, consider the inlet and outlet conditions in the experiments reported here. The inlet air delivered to the chambers was at 18°C and saturated, and the outlet gas during the period of temperature feedback control generally exceeded 50°C and was saturated. Given a suitable combination of set point and temperature sensor position in a field pile, similar inlet and outlet conditions could be obtained (assuming unusually humid and constant inlet air). In this circumstance, the overall temperature differential is similar in the laboratory and field, but the vertical gradient (degrees Celsius per meter) is much steeper in the laboratory. This type of vertical boundary has the effect of compressing 2 to 3 m of airflow pathway through the matrix into 0.4 m.

In the second type of boundary condition, the 0.4-m-high vertical cross-section in the experimental chamber corresponds to a 0.4-m-high fraction of the full field height. Consider, for example, a fraction bounded by horizontal planes at heights of 1.0 and 1.4 m. Suppose that a set point is assigned to the laboratory system to provide an outlet temperature of 40°C, to mimic a nominal temperature at the 1.4-m height in the field (the full height is 2 to 3 m, and the gas exit temperature is 60°C). Then, the inlet air temperature (at saturation) must be varied dynamically to slightly lag the temperature immediately above the point of air entry into the matrix. Air preconditioning thereby substitutes for passage through the bottommost 1 m of composting matrix. Our composting physical model was not designed to provide the second type of vertical boundary condition.

A qualitative comparison is possible between composting system behavior in the laboratory and the field, based on observations from this study and those reported earlier on similarly controlled (temperature feedback) field piles. The field piles relied on in this comparison were designated A (16); 7 (17); 8 (12); 9A (13); and 11A, 11B, and 11C (19). They consisted of primary (settled) wastewater sludge cake in admixture with either wood chips or recycled sludge-derived compost. The initial wet weight of these piles ranged from approximately 4 to 36 metric tons. In this laboratory-field comparison, chamber A was emphasized because it represented field conditions better.

The following qualitative behavioral patterns were common to the composting systems in both the laboratory and field. During the initial period of scheduled base-line ventilation, the temperature ascended to the set-point level and engaged feedback control. Temperature persisted at the set-point level for a time and then gradually descended. Demand for ventilation increased, decreased, and eventually ceased, disengaging temperature feedback control. During the temperature ascent, the level of residual O_2 declined; but once feedback control became engaged, the level recovered to within a small percentage of the ambient value. CO_2 followed an obverse pattern. A shallow, vertical temperature gradient established early in the initial period of base-line-scheduled ventilation was greatly steepened with the engagement of feedback control. The vertical gradient again became shallow with the later disengagement of feedback. A terminal period of base-line ventilation was characterized by high levels of residual O_2 and a gradual temperature descent. Horizontal gradients were slight. Finally, the extent of water removal and drying reflected a major ventilative role in heat removal and a minor conductive one. In the qualitative terms summarized above, composting system behavior in the laboratory and field was similar.

In the laboratory, a thin surface layer at the top of the composting material was uniformly wet. In the field, surface wetness may be patchy (our own usual observation) or uniform (23). Uniform surface wetness in the laboratory results from a more uniform airflow through the matrix. More fundamentally, as the gas emerges from the matrix it encounters lower bulkhead temperatures in an enclosed space. This causes condensation without the possibility for revaporization. In the field the gas encounters ambient air, which, depending on the weather, might result in dissipation of the vapor.

Two groups of investigators (2, 15) have provided detailed vertical temperature profiles at full-scale, deliberately ventilated composting facilities in routine operation. These profiles demonstrate ventilation-induced temperature gradients in the matrix along the airflow pathway, in correspondence to our own observations in the laboratory and field. Curiously, in a more recent report (20), one of these groups of investigators ascribed the establishment of such a temperature gradient in field piles to ill-controlled experimental conditions.

Finally, the composting physical model described here, along with constant-temperature (21) and adiabatic (24) apparatuses, represent an array of experimental devices for studying different aspects of self-heating in matrix systems (Table 1). While these devices share certain characteristics, each is distinct with respect to the management of heat flow. Whereas the composting physical model is designed to simulate a real process, the constant-temperature and adiabatic apparatuses are designed to provide experimental conditions that have no obvious real-world analogs. This comparative analysis is developed to help place the composting physical model in perspective.

TABLE 1. Conceptual and technical summary of laboratory devices for studying different aspects of self-heating in matrix systems

Device	Goal	Conduction control			Ventilation control			Water status trend	Cause of microbial self-limitation	Reference
		Objective	Experimental vessel surroundings	Temp control of surrounding fluid	Objective	Conditioning of inlet air	Δt and temp gradient along airflow pathway[a]			
Adiabatic apparatus	Study idealized self-heating	Dynamically minimize conduction	No insulation, water	Dynamic, based on temperature differential	Supply O_2 and remove CO_2; minimize heat removal	Dynamically equilibrate to temperature of surroundings and saturate	Both negligible	Becomes wetter	Harsh temperature	Walker and Harrison (24)
Constant temperature apparatus	Isolate temperature as an experimental variable	Maintain a temperature floor conductively	No insulation, water	Static, using conventional thermostat	Supply O_2 and remove CO_2; minimize heat removal	Equilibrate to temperature of surroundings and saturate	Both negligible	Becomes wetter	Eventual substrate depletion	Rothbaum (21)
Composting physical model	Simulate composting process as managed ventilatively for a high rate of activity[b]	Dynamically minimize conduction[c]; maintain ventilation-induced temperature gradient	Insulation, air	Dynamic, based on instantaneous conductive heat flux[c]	Remove heat in reference to temperature ceiling; supply O_2 and remove CO_2	Maintain constant ambient-like temperature and saturate	Both substantial; gradient variably steep	Becomes dryer	Eventual substrate and/or water depletion	This report

[a] Δt is the elevation of outlet gas enthalpy relative to that of inlet air.
[b] Goal adopted in the present study; other goals can be accommodated.
[c] Refers to chamber A.

Thermodynamically, composting is an open system in that matter (gases) and heat are exchanged with the environment (3). The heat exchange is via ventilative mechanisms and conduction. With the process controlled as described here, most of the exchange is via ventilation. Material undergoing self-heating in a constant-temperature apparatus is also an open system, but the idea is for the heat flow to be solely conductive. Ventilative heat flow is nearly eliminated through the air preconditioning regimen (which differs from that of the composting physical model). An adiabatic system is one in which matter but not heat can be exchanged with the environment. This condition is approached through dynamic preconditioning of the air and temperature control of the surroundings. Again, the intention is to eliminate ventilative heat flow. As a consequence, in the adiabatic apparatus the self-heating temperature ascent is, ideally, unattenuated by heat loss. Note that the presence or absence of a ventilation-induced temperature gradient along the airflow pathway is indicative of the particular air preconditioning regimen.

Constant-temperature and adiabatic experimentation has elucidated important relationships that are operative in composting. For example, the constant-temperature approach was used to study microbial population structure at different temperatures (22) and the boundary between biotic and abiotic self-heating (21). The adiabatic approach may represent the early temperature come-up stage of composting, but not later stages, reasonably well (14). Nonetheless, as seen in Table 1, these forms of self-heating experimentation are distinct from each other and from composting simulation per se. In investigating different theoretical and practical aspects of self-heating, the distinctions among these systems should be carefully observed.

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