SYNOPSIS

RESEARCH INTO DUAL DIGESTION

Over the past 10 years the Water Research Commission (WRC) has recognized the potential benefits of the dual digestion system for South Africa where anaerobic digestion is the preferred method of sludge stabilization. Accordingly, from 1981 to 1984 under WRC sponsorship, the Johannesburg City Council (JCC) undertook a pilot plant study into the performance of the autothermal thermophilic aerobic reactor oxygenated with pure oxygen. As a consequence of the encouraging results obtained in this study (Trim and McGlashan, 1984; Trim, 1984), in 1987 the WRC and Milnerton Municipality supported a full scale evaluation of dual digestion (45 m^3 pure oxygen oxygenated aerobic reactor and 600 m^3 anaerobic digestor) at Milnerton's Potsdam Wastewater Treatment Works, with scientific and academic input by the Division of Water Technology of the CSIR and the Department of Civil Engineering, of UCT. In this evaluation a number of important considerations needed to be addressed such as

(1) oxygen requirements and oxygen utilization efficiency with pure oxygen and air oxygenation,

(2) minimum retention time that can be achieved in the aerobic reactor and in the anaerobic digestor without compromising the attainment of thermophilic temperature in the reactor and VS removal, gas production and sludge stability in the digestor,

(3) temperature control of the aerobic reactor and anaerobic digestor,

(4) efficacy of pathogen inactivation and mode of operation to prevent recontamination,

(5) dewaterability of the anaerobically digested sludge,

(6) operation and economic evaluation of the system.

In this thesis, the results obtained pertaining to operation and performance of the Milnerton aerobic reactor are presented in detail. Also, the observed results are generalized and, based on the observed general principles, a design procedure and a simulation algorithm and computer programme for pure oxygen and air oxygenated reactors are developed, in accordance with objectives (1) to (3) above.

KINETICS OF BIOLOGICAL HEAT GENERATION

In order to meet objectives (1) to (3) above for the aerobic reactor, it was necessary to examine the kinetics of biological heat generation. In this regard it was realized during the investigation that a distinction needs to be made between the objectives of the thermophilic aerobic reactor in dual digestion and thermophilic aerobic digestion as a stand alone process. In the latter, the objective is to reduce the sludge energy as measured by VS removal; accordingly the process kinetics are defined in terms of a VS degradation rate, and from it a retention time to achieve a specified VS removal can be calculated. Also, the rates of biological heat generation and oxygen utilization are both related proportionally to the VS degradation rate. For the kinetics to be controlled by the VS degradation rate, the process needs to be operated under oxygen sufficient conditions. This approach is unproductive for modelling the aerobic reactor in dual digestion principally because it was found in this investigation that (1) the reactor was not operated under oxygen sufficiency conditions but under oxygen limiting conditions and (2) very little VS was removed in the reactor even though large quantities of biological heat were generated. Accordingly, because (1) biological heat generation theoretically can be shown to be stoichiometrically related to oxygen consumption rate and (2) the reactor is operated under oxygen limiting conditions, it was proposed that the oxygen supply rate and sludge oxygen consumption rate are the most useful parameters for operation, control, design and simulation of the aerobic reactor. Therefore the principal objective of the research became to substantiate this proposal by (1) verifying direct proportionality between the rates of biological heat generation and oxygen consumption via the specific heat yield (Y_H, MJ/kgO) and (2) demonstrating that with the oxygen supply rate, instantaneous and complete control of the reactor sludge temperature could be obtained.

EVALUATION OF AEROBIC REACTOR

In order to measure the specific heat yield (Y_H), accurate heat and oxygen mass balances needed to be made over the aerobic reactor. Because the aerobic reactor was batch fed on a draw and fill basis, (to avoid contamination of the effluent sludge with influent sludge; this incidentally, also provided an accurate means of sludge flow measurement), the reactor temperature fluctuated over a batch cycle resembling a saw-tooth pattern with 3 phases i.e. (1) a sludge transfer phase (draw) of 4 min, (2) a feeding phase (fill) of 3 min and (3) a heating phase of 2 to 6h depending on the reactor retention time. By measuring during the heating phase, (1) the sludge temperature increase rate, which is proportional to the sludge enthalpy increase rate (H_{net}), (2) the oxygen injection recirculation pump mechanical heat input rate (H_{mi}), (3) the wall heat loss rate (H_{we}) and (4) the vent gas water vapour heat loss rate (H_{ve}), the biological heating rate (H_{bi}) could be determined. Then by dividing H_{bi} by the mass oxygen consumption rate (O_c) obtained from the oxygen mass balance over the same heating period, the specific heat yield (Y_H) was calculated.

To measure the oxygen consumption rate required careful monitoring of the influent and vent gas volumetric flow rates. With regard to the vent gas, the total vent gas flow was collected, dehumidified to dry it and measured in a town's gas meter. The water vapour removed from the vent gas in condensers was collected and from this the water vapour heat loss rate was calculated. The oxygen and carbon dioxide mass and molar flow rates in the vent gas were obtained by measuring the oxygen content of the dried vent gas at the gas meter.

Apart from the heat and oxygen mass balances, influent sludge VS and COD concentrations also were measured to check whether or not the rates of biological heat generation or oxygen consumption correlated with VS or COD removal rates.

AEROBIC REACTOR RESULTS

Over a period of 8 months, 116 heat and oxygen mass balances were done over the aerobic reactor. During this time the operating conditions differed widely viz. reactor sludge temperature 54 to 69°C, retention time 1.2 to 3d, average ambient temperature 8 to 30°C and oxygen supply rates (OSR) from 0.13 to 0.44 $kgO/(m^3.h)$ giving oxygen transfer rates (OTR, or equivalently sludge oxygen consumption rate, O_C) from 0.13 to 0.39 $kgO/(m^3.h)$ and oxygen transfer efficiencies (OTE = OTR/OSR) from 1.00 to 0.80 respectively. From these tests the following results were obtained:

(1) Biological heat generation rate was directly proportional to the oxygen

transfer rate (OTR), or equivalently the sludge oxygen consumption rate (O_c). The constant of proportionality is the specific heat yield (Y_H) and was measured to be 12.77 ± 0.58 MJ/kgO. This value conforms closely to thermodynamically and bioenergetically calculated values. The value was found to be independent of reactor sludge temperature and retention time but was slightly dependent on oxygen limitation (defined as 1-OTR/OUR), increasing as oxygen limitation increased.

(2) Reactor sludge temperature increases could be completely, and instantaneously, controlled by means of the oxygen supply rate (OSR) *for as long as the reactor was oxygen limited* i.e. while the oxygen transfer rate (OTR) was less than the maximum biological oxygen utilization rate (OUR). For the Milnerton sludge, which was a mixture of primary and humus (biofilter) sludge, OUR was measured to be about 0.38 kgO/(m^3.h) at an average concentration of 30 kgVS/m^3. Step increases in OSR as high as 330% [from 0.13 to 0.43 kgO/(m^3.h)] which increased OTR and hence the biological oxygen consumption rate by 300% [from 0.13 to 0.39 kgO/(m^3.h)] caused an immediate (<2h) increase in the biological heat generation rate (H_{bi}) and hence an increasing reactor sludge temperature. In the same way, decreasing the OSR caused an immediate decrease in H_{bi} and a decreasing reactor sludge temperature. Increases in OSR did not cause an equivalent increase in OTR because, as OTR increased so OTE (= OTR/OSR) decreased. This was the case with the Milnerton Vitox pumped recirculation pure oxygen injection oxygenation system, and probably also will be the case with other pure oxygen and air oxygenation systems. This aspect is of considerable significance in design.

(3) Respiration quotient i.e. mole CO_2 generated per mole O_2 utilized was 0.66 instead of 1.0 often assumed. From this it appeared that the oxidation reactions in the aerobic reactor were not simply those of VS degradation.

(4) Vent gas was saturated with water vapour at all vent gas flow rates.

(5) COD and/or Volatile Solids (VS) removal rates were poor parameters for (i) quantifying the biological heat generation rate and (ii) controlling the reactor sludge temperature because the tests (i) are prone to significant variability when dealing with sewage sludges and (ii) take too long to give a

result.

The close correlation, and rapidity of response, between the biological heat generation rate and the oxygen transfer rate make the OTR a pivotal parameter in design and simulation of autothermal thermophilic aerobic reactors in dual digestion.

DESIGN AND SIMULATION OF THE AEROBIC REACTOR

Aerobic reactor design and simulation procedures were derived from the results of the Milnerton aerobic reactor performance. These are founded on the basic heat and mass balance principles and accordingly are suitable for general application to aerobic reactor design. Therefore, whereas pure oxygen oxygenation was used on the Milnerton reactor, the derived design and simulation procedures are general and apply to reactors oxygenated also with air or oxygen enriched air.

The design procedure is based on the solution of the steady state heat balance across the reactor. Such a heat balance yields a constant temperature for the reactor sludge and is applicable only to reactors that are continuously fed. However, in practice, the reactor is batch fed to avoid recontamination of pasteurized sludge. This causes the reactor sludge temperature to fluctuate between 2 and 4°C per batch cycle. Nevertheless, despite batch feeding, the steady state approach is adopted for design because it greatly simplifies the design procedure.

Two objectives need to be met by the aerobic reactor in dual digestion, viz. (1) pasteurization by exposure of the sludge to a minimum temperature for a minimum length of time generally above 60°C for 2h or above 70°C for 30 min and (2) pretreatment through oxygen limitation for enhanced performance of the anaerobic digestor. The literature does not define the temperature and the degree of oxygen limitation at which sludge pretreatment is best accomplished, nor could this be established at Milnerton. Thus the approach to design is to ensure that (1) the specified pasteurization temperature and times are maintained in the reactor, and (2) the sludge is oxygen limited, i.e. the OTR [kgO/(m^3.h)] to the sludge by the oxygenation system is controlled at a lower value than the sludge's maximum OUR [kgO/(m^3.h)]. Not only is oxygen limitation important for sludge pretreatment but, as mentioned above, also for reactor sludge temperature control. Sludge stabilization (i.e. VS removal) is *not* an objective of the aerobic reactor; this is accomplished in the anaerobic digestor. Therefore the oxygen supply rate is governed solely by the requirement of generating sufficient heat biologically to achieve the pasteurization specifications.

Accepting that design of the aerobic reactor centres on minimizing the retention time through maximizing the heat sources (i.e. biological heat generation and mechanical heat input) and minimizing the heat losses (i.e. wall heat loss and vent gas water vapour and sensible heat losses) it is demonstrated with the aid of the steady state heat balance that 3 parameters are of crucial importance, viz:

(1) The sludge oxygen utilization rate (OUR), which fixes the maximum biological heat generation rate through the specific heat yield (Y_H).

(2) The oxygen transfer rate (OTR) of the oxygenation system. The actual biological heat generation rate is directly proportional to the OTR through the specific heat yield (Y_H). The OTR should be less than the OUR to ensure (1) sludge pretreatment through oxygen limitation and (2) reactor sludge temperature control through control of the oxygen supply rate (OSR).

(3) The oxygen transfer efficiency (OTE) of the oxygenation system. For a particular pure oxygen or air oxygenation system at a given OTR, the OTE controls the vent gas volumetric flow rate; the lower the OTE the greater the vent gas flow rate and hence the greater the vent gas heat losses (via water vapour and sensible heats).

At a certain OTR and mechanical heat input, the heat sources are fixed. If OTE is high (>0.80) and oxygenation is with pure oxygen, the vent gas heat losses are small with the result that most of the heat generated can be lost via hot effluent sludge thereby allowing short retention times (~ 1.25 to 2d); if OTE is low (0.10–0.20) and oxygenation is with air, then vent gas heat losses are high with the result that much less heat can be lost via the hot effluent sludge thereby forcing long retention times (4–6d). At Milnerton, where the sludge OUR was observed to be around 0.38 kgO/(m^3.h) and high OTR's and OTE's of 0.37 kgO/(m^3.h) and > 0.80 respectively were achieved with the use of pure oxygen, the vent gas heat losses were very low allowing 1.25d retention time operation and reactor temperatures above 60°C. In contrast, with air oxygenation, OTR's and OTE's tend to be considerably lower [e.g. at Athlone, 0.14 kgO/(m^3.h) and 0.12 respectively, Pitt, 1990] and the major part of the heat generated is lost via the vent gas with the result that only a minor part of the heat can be lost via hot effluent sludge thereby forcing long retention time operation to maintain temperatures above 60°C.

Biological heat generation has the drawback in that increasing its rate requires increases in OTR. Increases in OTR require increases in oxygen or air supply rates (OSR) which, together with the reduction in OTE usually caused by increases in OTR, causes larger vent gas heat losses. In contrast to biological heat generation, supplementary heat sources such as (1) heat exchange between reactor effluent and feed sludge (2) increased mechanical heat input, or (3) anaerobic digestor gas combustion, have the effect of increasing the heat sources without increasing the heat losses, and therefore allow a *pro rata* reduction in retention time.

The design procedure described above is based on the steady state heat balance which accepts that the reactor sludge temperature is constant and therefore applies only to a continuously fed reactor. Pasteurization requires the reactor to be batch fed, resulting in a continuously changing reactor sludge temperature over about 3°C in a saw-tooth pattern, decreasing at times of feeding and increasing between the feeding times, with the result that the reactor is not at steady state. The error arising from assuming steady state conditions is small and well justified by the simplifications in the heat balance it affords. The saw-tooth temperature profile can only be determined by solving the unsteady state heat balance by a forward integration method. This is dealt with in this thesis and an algorithm and computer programme are presented which solve the unsteady heat balance in order to simulate the temperature profile of the batch fed aerobic reactor. For specified input conditions identical to those observed in the Milnerton reactor, the simulation programme is shown to simulate the reactor sludge temperature profile to within 0.5°C. Whereas the steady state design allows only the required pasteurization temperature to be specified, the simulation programme allows both the sludge pasteurization temperature and the undisturbed sludge detention period to be defined, the latter in terms of the interval between consecutive batch feeds.