3.1.3 Mass balance of the organic material

When an activated sludge system receives a constant load of organic material, a sludge mass will develop that is quantitatively and qualitatively compatible with this load and the prevailing operational conditions. Under steady state conditions there is no accumulation of influent organic material, therefore it will either be discharged with the effluent or the excess sludge, or it will be transformed into inorganic products by oxidation. Hence the daily applied mass or flux of influent organic material will be equal to the sum of the fluxes of (1) organic material in the effluent, (2) organic material contained in the excess sludge, and (3) the flux of oxidised material. There are basically only two transformations possible for the organic material in the activated sludge system:

- Transformation into organic sludge by biochemical (anabolism, decay) or physical processes (flocculation, adsorption);
- Oxidation into inorganic products.

Fig. 3.2 shows a schematic representation of a basic activated sludge system. It is concluded that the influent organic material is divided in the activated sludge system into three distinct fractions, identified as follows:

- Part of the influent organic material is not removed from the liquid phase and leaves the activated sludge system together with the effluent (MS_{te} in Fig. 3.2);
- A second fraction of the organic material is transformed into organic sludge and is discharged as excess sludge (MS_{xv});
- The third fraction of the organic material is oxidised (MS_o).

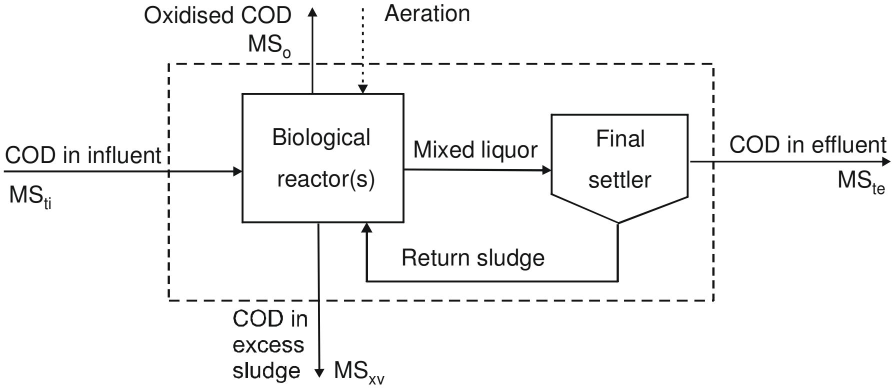

Figure 3.2 Flow diagram of the simplified activated sludge system and the associated COD fluxes

As all fractions are generated from the influent organic material (MS_{ti}), one has:

$$MS_{ti} = MS_{te} + MS_{xv} + MS_o \qquad (3.6)$$

Where:

MS_{ti} = daily applied COD mass (kg $COD.d^{-1}$)
MS_{te} = daily COD mass in the effluent (kg $COD.d^{-1}$)
MS_{xv} = daily COD mass in the excess sludge (kg $COD.d^{-1}$)
MS_o = daily mass of oxidised COD (kg $O_2.d^{-1}$ or kg $COD.d^{-1}$)

Equation (3.6) expresses that in an activated sludge system under steady state conditions the flux of influent organic material is equal to the fluxes of organic material or its products that leave the activated sludge system. In order to verify the validity of Eq. (3.6) it is necessary to transform the fluxes MS_{ti}, MS_{te}, MS_{xv} and MS_o into experimentally measurable parameters. The COD fluxes in the influent and effluent can be transformed easily:

$$MS_{ti} = Q_i \cdot S_{ti} \tag{3.7}$$

and

$$MS_{te} = (Q_i - q) \cdot S_{te} \tag{3.8}$$

Where:

Q_i = influent flow ($m^3.d^{-1}$)
q = excess sludge flow ($m^3.d^{-1}$)
S_{ti} = influent COD (mg $COD.l^{-1}$)
S_{te} = effluent COD (mg $COD.l^{-1}$)

The flux of organic material discharged as excess sludge can be determined from the volatile sludge concentration and the dissolved COD concentration in the excess sludge. Knowing that there is a proportionality between the volatile solids mass and its COD (f_{cv} = 1.5 mg COD.mg VSS^{-1}) one has:

$$MS_{xv} = q \cdot (f_{cv} \cdot X + S_{te}) = q \cdot (f_{cv} \cdot X_v) + q \cdot S_{te} \tag{3.9}$$

In Eq.(3.9) it is assumed that the dissolved COD concentration in the excess sludge is equal to the effluent COD concentration, a supposition that will prove to be justified. The flux of oxidised organic material, MS_o, can be determined from the consumption of dissolved oxygen (DO) in the mixed liquor. By definition, in order to oxidise 1 kg of COD there is an oxygen requirement of 1 kg of O_2. Hence, the flux of oxidised organic material will be numerically equal to the flux of consumed oxygen. The latter flux is equal to the product of the reactor volume and the oxygen uptake rate (OUR). The OUR is the mass of oxygen consumed per unit of time in a unit volume of mixed liquor and can be determined experimentally.

The principle of the OUR test is the following: while the influent flow rate continues as normal, the aeration of the mixed liquor is interrupted. After the interruption the decrease of the DO concentration with time (due to consumption) is observed and -preferably- registered. The decrease of the DO concentration is linear with time and the gradient of this linear function is equal to the OUR. A more detailed description of the OUR test and its limitations can be found in appendix 1 and Section 3.2.

The value of the OUR determined as described above equals the total oxygen uptake rate. However, part of the consumed oxygen may have been used for nitrification in the activated sludge system. It is possible to estimate the consumption rate for nitrification (O_n) from the increase of the nitrate concentration in the activated sludge system. Thus the OUR for the oxidation of organic material (O_c) can be determined indirectly, by subtracting the oxygen uptake rate for nitrification (O_n) from the total oxygen uptake rate (O_t):

$$O_c = O_t - O_n \tag{3.10}$$

Where:

O_t = total OUR (mg $O_2.l^{-1}.d^{-1}$)
O_n = OUR for nitrification (mg $O_2.l^{-1}.d^{-1}$)
O_c = OUR for oxidation of organic material (mg $O_2.l^{-1}.d^{-1}$)

Having established the value of O_c, the flux of oxidised organic material is determined as:

$$MS_o = O_c \cdot V_r \tag{3.11}$$

Where V_r = reactor volume

Now, using the expressions of Eqs. (3.7 to 3.11) in Eq. (3.6), one has:

$$Q_i \cdot S_{ti} = (Q_i - q) \cdot S_{te} + q \cdot (f_{cv} \cdot X + S_{te}) + O_c \cdot V_r \text{ or}$$

$$S_{ti} = S_{te} + (q/Q_i) \cdot f_{cv} \cdot X_v + O_c/R_h \tag{3.12}$$

Where R_h = liquid retention time = V_r/Q_i

In Eq. (3.12) all variables are measurable, so that the validity of the equation can be verified experimentally. However, in general it will be unlikely that an exact equality of the two sides of Eq. (3.12) is found. This is partly due to the fact that the tests are subject to experimental errors, but also because the activated sludge system usually is not operated under rigorously steady state conditions, which is a presupposition for the validity of Eq. (3.12). For this reason the recovery factor for organic material is defined as:

$$B_o = (MS_{te} + MS_{xv} + MS_o)/MS_{ti} = (S_{te} + (q/Q_i) \cdot f_{cv} \cdot X_v + O_c \cdot R_h)/S_{ti} \tag{3.13}$$

From Eq. (3.13) it can be concluded that the theoretical value of the recovery factor is identical to one. Due to experimental errors and spontaneous fluctuations in the physiological activity of the sludge, the value of B_o will deviate from its theoretical value. However, when the average value of a series of experiments over a period (for example a few weeks) is considered, the deviation between the theoretical and the experimental value of the recovery factor will typically be less than 10 percent. Stated differently, if there is a systematic difference between the theoretical and experimental value of B_o, there is good reason to suspect that one or more of the tests used to calculate B_o is not being carried out properly or that the activated sludge system is not yet operating under steady state conditions. On the other hand, a closing mass balance (i.e. an experimental B_o between 0.9 and 1.1) is a clear indication that the system was operating under steady state conditions and that the tests to determine B_o were carried out correctly. Hence, the verification of a closing mass balance is powerful indication that the experimental data are reliable.

When BOD is used (the alternative parameter for organic material) it is not possible to verify if the mass balance closes. In the previous section it was shown that in the activated sludge system a non-biodegradable sludge fraction, the endogenous residue, is generated from the decay of active sludge. Part of the biodegradable influent material (with associated BOD demand) is converted into non-biodegradable endogenous residue (without associated BOD demand) so that the mass balance cannot close: the activated sludge system is a "BOD sink" in which BOD disappears without corresponding oxidisation.

The value of the BOD flux in the effluent and in the excess sludge, together with the oxygen consumption for the oxidation of biodegradable organic material in the influent, will always be smaller than the BOD flux in the influent. The fact that it is not possible to verify whether the mass balance closes, when BOD is used as a quantitative parameter for organic material, is a very serious disadvantage for this test. This is one of the reasons that in the present text COD rather than BOD is used to quantify the concentration of organic material.

For the analysis of the behaviour of the activated sludge system, it is convenient to have explicit expressions for the different COD fractions (l) discharged with the effluent, (2) discharged as excess sludge, and (3) oxidised. To find these expressions Eq.(3.13) may be rewritten as:

$S_{te}/S_{ti} + (q/Q_i) \cdot f_{cv} \cdot X_v/S_{ti} + R_h \cdot O_c/S_{ti} = B_o$ or

$$mS_{te} + mS_{xv} + mS_o = B_o \tag{3.14}$$

Where:

mS_{te} = S_{te}/S_{ti}
= fraction of the influent COD discharged in the effluent
mS_{xv} = $(q/Q_i) \cdot f_{cv} \cdot X_v/S_{ti}$
= fraction of the influent COD discharged with the excess sludge
mS_o = $R_h \cdot O_c/S_{ti}$
= fraction of the influent COD oxidised in the process.

The numerical values of these fractions are of very great importance for a description of the behaviour of the activated sludge system: the fraction mS_{te} is indicative for the effluent quality, the value of mS_{xv} is representative for the sludge production (and consequently for the design of the excess sludge treatment units) and the mS_o value is a measure for the oxygen demand in the process (and hence for the oxygenation capacity to be installed).

As an example for the data of set I in Table 3.2 one can calculate the following values for the three fractions defined above:

$mS_{te} = S_{te}/S_{ti} = 127/730 = 0.17$
$mS_{xv} = (q/Q_i) \cdot f_{cv} \cdot X_v/S_{ti} = 3.33/16 \cdot 1.5 \cdot 1060/730 = 0.45$
$mS_o = (V_r/Q_i) \cdot OUR_c/S_{ti} = 10/16 \cdot 20.3 \cdot 24/730 = 0.42$

The sum of the three fractions is equal to the value of the recovery factor B_o.

$B_o = 0.17 + 0.45 + 0.42 = 1.04$

In Table 3.3 the values of the fractions mS_{te}, mS_{xv} and mS_o have been calculated for each of the sets of experiments in Table 3.2.

Table 3.3 Values of the fractions mS_{te}, mSX_{xv} and mS_o in the 5 experimental sets of Table 3.2

Exp.	mS_{te}	mS_{xv}	mS_o	B_n	R_s
I	0.17	0.45	0.42	1.04	3
II	0.13	0.37	0.52	1.02	10
III	0.12	0.23	0.68	1.03	20
IV	0.20	0.29	0.59	1.08	20
V	0.10	0.17	0.69	0.97	30

The experiments show that the operational conditions have an influence on the values of the fractions, especially in the case of mS_{xv} and mS_o. The mass balance for organic material allows the determination of the values of the COD fraction in the effluent, in the excess sludge and oxidised in the reactor. However, in practice it is of more interest to be able to **predict** the division of the influent organic material over the three fractions, rather than to calculate their values.

In order to be able to do so, it is necessary to develop a model to describe the behaviour of the activated sludge system in a quantitative manner, so that theoretical values for the fractions mS_{te}, mS_{xv} and mS_o can be calculated. In the following sections a model is developed that allows estimations of the three fractions as a function of the concentration and composition of the influent organic material and the operational conditions of the activated sludge system.