Chapter 23

Tower-Shaped Reactors for Aerobic Biological Waste Water Treatment

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List of Symbols

a	m^2/m^3	volume-related interfacial area
c'	kg/m^3	O_2 saturation concentration at gas inlet
c''	kg/m^3	O_2 saturation concentration at gas outlet
$\mathbb{D}$	m^2/s	diffusivity of O_2 in water
d_1	m	diameter of gas flow channel in nozzle
d	m	diameter of liquid flow channel in nozzle
E	kg/kWh	oxygen transfer efficiency
g	m/s^2	acceleration due to gravity
G	kg/h	oxygen transfer rate
h	m	injector clearance
H	m	height of liquid
k_L	m/s	mass transfer coefficient
p_1	N/m^2	pressure of ambient
p_2	N/m^2	pressure of gas at inlet of reactor
P	W	compressor power
P_L	W	pump power
q	m^3/s	gas flow rate
q_L	m^3/s	liquid flow rate
V	m^3	volume of reactor
Δc_m	kg/m^3	mean logarithmic concentration difference
Δp	N/m^2	pressure drop of gas in nozzle
Δp_L	N/m^2	pressure drop of liquid in nozzle
ν	m^2/s	kinematic viscosity of gas
ν_L	m^2/s	kinematic viscosity of liquid
ϱ	kg/m^3	density of gas
ϱ_L	kg/m^3	density of liquid
σ	N/m	surface tension

$Eu \equiv \frac{\Delta p\, d_1^4}{\varrho q^2}$	Euler number for gas flow
$Eu_L \equiv \frac{\Delta p_L d^4}{\varrho_L q_L^2}$	Euler number for liquid flow
$Re_L \equiv \frac{q_L}{\nu_L d}$	Reynolds number for liquid flow in nozzle
$X \equiv \frac{P_L/q_2}{\varrho(\nu g)^{2/3}}$	gas dispersion number
$Y \equiv \frac{G}{H q_1 \Delta c_m}\left(\frac{\nu^2}{g}\right)^{1/3}$	gas sorption number

23.1 Introduction

23.1.1 Abstract

The aeration of bacterial cultures in activated sludge tanks is the main operation in aerobic biological waste water purification with which process engineers have concerned themselves over the past ten years. The study of this process has shown that efficient utilization of atmospheric oxygen can only be achieved by means of relatively tall liquid columns and a correspondingly long residence time of the gas phase. This consideration, along with the need for space-saving plant designs and odorless, noiseless operation, led in Britain and Canada to shaft-like designs for the activated sludge tank (ICI – "deep shaft process"). Parallel developments in the Federal Republic of Germany resulted – simply because of the soil conditions – in tower-shaped reactors. Bayer AG, Leverkusen, for example, developed the concept of "Tower Biology", while Hoechst AG, Frankfurt, came up with the "Biohigh Reactor".

This chapter is devoted mainly to the *process engineering* research carried out in order to develop tower-shaped reactors. Details are given of the criteria by which the aeration devices (injectors) were developed and the factors that led to their optimization. It was essential here that special attention should be paid to the physical, process-related and geometric factors affecting the process of coalescence, which runs counter to dispersion of the gas. The high efficiency of the technical-scale injectors developed is indicated by the fact that, under the coalescence-promoting conditions encountered with the usual type of effluent, they achieve an efficiency $E \approx 3.8$ kg O_2 per kWh and 80% O_2 utilization (4% by volume O_2 in the off-gas) with a liquid height of 17 meters, calculated on standard conditions.

Finally, a description is given of biological waste water treatment plants, either completed or still under construction,

which have been designed according to the principle of the tower-shaped activated sludge tank.

23.1.2 Background

The aeration of a bacterial culture ("activated sludge") in a sewage treatment unit (activated sludge basin or tank) so far has been regarded as the most important engineering operation process in aerobic biological waste water treatment, especially as it may account for up to 30% of the running costs. The function of the aeration devices is to ensure that the bacterial culture is supplied with sufficient oxygen while at the same time maintaining an adequate flow velocity in the treatment unit so that no biomass is deposited on the bottom, where it might putrefy. For decades, activated sludge units were normally constructed in the form of flat, open basins; these take up a large space and – particularly when surface aeration is employed – are a constant source of troublesome noise and unpleasant odors (aerosol emission).

It was obvious that, if the activated sludge units were to be built in the form of a tower or shaft, not only would the aeration efficiency improve but the plant would also take up much less space and the odor emission could be considerably reduced. Such a unit could easily be covered over and, in view of the height of the liquid column above the aeration devices, oxygen from the gaseous phase (air) would be absorbed by the liquid under a higher system pressure. These ideas were put into practice in the seventies in Britain and Canada in the form of the ICI "Deep Shaft Process", while in the Federal Republic of Germany tower-shaped activated sludge units (Bayer AG's Tower Biology®, Hoechst AG's BIOHOCH Reactor®) were developed.

This chapter describes the problems associated with the concept of the tower-shaped reactor and the solutions which finally made their industrial-scale realization possible.

23.2 Choice of Aeration System

The central feature of a tower-shaped activated sludge tank is its aeration system, which has to ensure that the biomass is supplied efficiently with oxygen. This involves two requirements: (1) A high efficiency E (in kg/kWh) of the O_2 uptake must be guaranteed, combined with a minimum gas throughput in order to prevent foaming problems and to reduce the cost of any off-gas treatment (thermal or biological). This means (2) that a high degree of utilization of the atmospheric oxygen must be achieved, which is then reflected in the small O_2 molar fraction x'' in the off-gas.

These aims can be achieved through careful selection of process engineering parameters (shape of the aerator and its operating parameters) and of the height H of the liquid column, a geometric parameter. There can be no doubt that only what are known as volume aerators are suitable in tower-shaped reactors; stirrers cannot be used for obvious reasons. The only possibilities here are gas dispersers (porous aerators, static mixers) or two-phase nozzles (injectors). It should be remembered that the job of these aeration devices is not only to produce fine gas bubbles but, even more importantly, to distribute them rapidly and evenly over the entire cross-section of the activated sludge tank so that they cannot collide with each other as they rise to the surface and "coalesce" to form larger bubbles. It must also be noted that the swarms of gas bubbles in the tower have the function of maintaining an intensive liquid circulation that prevents precipitation of the flocs while at the same time ensuring sufficient back-mixing of the liquid over the height of the tower. This is the only way to obtain an O_2 concentration gradient over the entire height that ensures intensive O_2 absorption near the bottom and prevents the escape of dissolved O_2 from the upper layers of the liquid column.

The aeration device chosen by Bayer AG was the injector. There were two reasons for this:

a) Good results had already been obtained in the 60s with a small type of injector (8/14 injector), which was used in basins 4 meters deep at the Dormagen factory.
b) In view of the *two* freely selectable process parameters (gas throughput *and* liquid throughput), it was reasonable to expect that injectors would be more effective than gas dispersers in mixing the gas bubbles quickly into the liquid volume and distributing them over the cross-section of the tower, thus reducing bubble coalescence.

Hoechst AG, too, opted for the use of two-phase nozzles right from the start, cf. Sect. 23.7.1.

23.3 Design Data for Injectors

Injectors are two-phase nozzles, in which the kinetic energy of the liquid propulsion jet is used to break up the gas into very fine bubbles. They are positioned just above the floor of the treatment tank, the height of the liquid column in the tank thus becoming a freely selectable parameter which can therefore be optimized. This arrangement means that the rising gas bubbles have to traverse the full height of the liquid column. If an injector is to be designed ideally for the required O_2 uptake, data must be obtained which permit the necessary process conditions – as far as mass transfer is concerned – to be calculated in advance and also indicate the power consumption. Sorption and pressure drop characteristics must therefore be compiled for the injector. These are representations of relevant test results based on the theory of similarity, the "sorption characteristics" serving to describe both the relationship between the absorption rate and the two process parameters (gas and liquid throughputs) and to allow for the effect of the coalescence behavior of the system on mass transfer. The term "system" here includes both the physical properties of the liquid and the position of the injector. Fine primary bubbles in a coalescence-promoting system do, of course, merge rapidly to form larger bubbles. This process also depends greatly on geometrical parameters.

23.3.1 Sorption Characteristic of an Injector [23.1]

23.3.1.1 Definition of $k_L a$

Mass transfer in a gas/liquid system is generally described in terms of the gross absorption rate equation:

$$G/V = k_L a \Delta c_m , \qquad (23.1)$$

which serves as a definition equation for the volume-related sorption coefficient $k_L a$:

$$k_L a \equiv \frac{G}{V \Delta c_m} , \qquad (23.2)$$

where

G/V	is volume-related mass transfer through the interface (in kg/m^3 s),
k_L	liquid-side mass transfer coefficient (in m/s),
a	volume-related interfacial area (in m^2/m^3), and
Δc_m	mean logarithmic concentration difference (in kg/m^3).

Δc_m is defined as:

$$\Delta c_m \equiv \frac{c' - c''}{\ln \dfrac{c' - c}{c'' - c}} . \qquad (23.3)$$

This assumes that the actual conditions are sufficiently far away from equilibrium, that the back-mixing of the gas phase is negligible and that back-mixing of the liquid is complete.

c' and c'' are the O_2 saturation concentrations corresponding to the O_2 content of the gas at the gas inlet and outlet, respectively; c is the O_2 concentration in the liquid.

The saturation concentration at the gas inlet,

$$c' = c_s x'(1 + 0.1\,H), \qquad (23.4)$$

with $x' = 0.21$ for air, depends only on the temperature and the height H (in m) of the liquid above the injector. But the saturation concentration at the gas outlet:

$$c'' = c_s x'', \qquad (23.5)$$

is also dependent on the O_2 molar fraction x'' in the off-gas, which is calculated from the absorption rate G and the air throughput q using the formula:

$$x'' = (q x' - G/\varrho_{O_2})/(q - G/\varrho_{O_2}). \qquad (23.6)$$

The gas throughput q (in m^3/s) and O_2 gas density ϱ_{O_2} (in kg/m^3) relate here to identical conditions (e.g., standard conditions).

The relationship between the O_2 saturation concentration c_s and the temperature can be obtained from the relevant tables.

23.3.1.2 Formulation According to the Theory of Similarity

When formulating the absorption characteristics according to the theory of similarity, it must be remembered that the definition of $k_L a$ as a volume-related intensive quantity implies three consequences:

1. Independence of geometric parameters (in view of the assumption that the gas/liquid system is quasi-uniform).
2. Independence of the material parameters of the gas (in view of the assumption $k_G \gg k_L$).
3. Formulation of the process parameters as intensive quantities.

The following material parameters of the liquid phase have to be taken into account:

ϱ	density of liquid,
ν	kinematic viscosity of liquid,
$\mathbb{D}$	diffusivity of O_2 in the liquid,
σ	surface tension of the liquid, and
S_i	material parameters that describe the coalescence behavior of the system and whose number and nature are as yet unknown.

With injectors, the gas throughput q and the liquid throughput q_L occur as (extensive) process parameters. Since the hydrodynamic behavior of bubble columns is given by the superficial velocity of the gas, $v = q/A$ with A as the cross-sectional area, this quantity can be used to advantage as a reasonably intensively, formulated process parameter. The liquid throughput q_L tells us nothing about its dispersing effect on the gas continuum. Instead of q_L we therefore select the power P_L of the propulsion jet throughput:

$$P_L = \Delta p_n q_L, \qquad (23.7)$$

where Δp_n is the pressure drop in the propulsion jet nozzle. Selection of P_L does, however, require a knowledge of the pressure drop characteristic, and thus we arrive at the intensive quantity P_L/q. The third process parameter is acceleration due to gravity g which, because of the extreme density differences within the gas/liquid system, must greatly affect the hydrodynamics of the process.

The quantity in question, $k_L a$, is therefore given by the following relationship:

$$\underset{\substack{\text{Target}\\ \text{parameter}}}{k_L a} = f(\underbrace{\varrho, \nu, \mathbb{D}, \sigma, S_i}_{\substack{\text{Material}\\ \text{parameters}}};\ \underbrace{v, P_L/q, g}_{\substack{\text{Process}\\ \text{parameters}}}) \qquad (23.8)$$

This relationship between nine dimensional quantities can be reduced by dimensional analysis to a relationship between $9-3=6$ numbers, because 3 basic units (mass, length, time) occur in their dimensions. With regard to the parameters designated S_i, which describe the coalescence behavior of gas bubbles in solutions, it should be noted that they are always converted by means of the parameters ϱ, ν, and g – regardless of their dimensions – to numbers based solely on physical properties. It follows that:

$$(k_L a)^* = \Psi[v^*, (P_L/q)^*, Sc, \sigma^*, S_i^*]. \qquad (23.9)$$

The dimensionless numbers are defined as follows:

$$(k_L a)^* \equiv k_L a (\nu/g^2)^{1/3} \qquad (23.10)$$

$$v^* \equiv v(g\nu)^{-1/3} \qquad (23.11)$$

$$(P_L/q)^* \equiv (P_L/q)/[\varrho(\nu g)^{2/3}] \qquad (23.12)$$

$$Sc \equiv \nu/\mathbb{D} \text{ (Schmidt number)} \qquad (23.13)$$

$$\sigma^* \equiv \sigma/[\varrho(\nu^4 g)^{1/3}] \qquad (23.14)$$

S_i^* ≡ dimensionless numbers allowing for the coalescence parameters S_i

When absorption takes place in the *same* material system and at constant temperature, the numbers Sc, σ^*, S_i^* remain constant and the relationship is reduced to:

$$(k_L a)^* = \Psi_1[v^*, (P_L/q)^*], \qquad (23.15)$$

with Sc, σ^*, $S_i^* = \text{const}$.

In many research projects on bubble columns with gas dispersers (porous or perforated plates), it has been found that $k_L a \propto v$ or $k_L a/v = \text{const}$ (gas disperser). This is an obvious finding from the physical point of view, if the definition equations for $k_L a$ and v are called to mind:

$$\frac{k_L a}{v} = \frac{G}{V \Delta c_m} \cdot \frac{A}{q} = \frac{G}{H q \Delta c_m}, \qquad (23.16)$$

with the column volume $V = HA$. The mass transfer rate G is proportional to the liquid height H, the gas throughput q, and the mean logarithmic concentration difference Δc_m.

We can assume that this also applies to injectors, when $P_L/q = \text{const}$ (identical gas bubble size distribution). Thus, the three-parameter function Eq. (23.15) is reduced by one parameter to give:

$$\frac{(k_L a)^*}{v^*} = \Psi_1\{(P_L/q)^*\} \text{ or} \qquad (23.17)$$

$$\frac{k_L a}{v}\left(\frac{\nu^2}{g}\right)^{1/3} = \Psi_1\left\{\frac{P_L/q}{\varrho(\nu g)^{2/3}}\right\}. \qquad (23.18)$$

With high bubble columns, more accurate allowance can probably be made for the influence of the gas throughput q (in $v = q/A$) if this is related to the mean system pressure:

$$q_1 = q/(1 + 0.05\,H), \qquad (23.19)$$

with H in m. The power P_L of the propulsion jet, however, affects a gas throughput that is subject to the system pressure at the level of the injector:

$$q_2 = q/[1 + 0.1(H-h)], \qquad (23.20)$$

with h in m being the injector clearance.

Taking this into account, the two numbers must be defined as follows:

$$Y \equiv \frac{G}{H q_1 \Delta c_m}\left(\frac{\nu^2}{g}\right)^{1/3}, \quad \text{sorption number} \qquad (23.21)$$

$$X \equiv \frac{P_L/q_2}{\varrho(\nu g)^{2/3}}. \quad \text{dispersion number} \qquad (23.22)$$

The object of the tests will be to determine the functional relationship:

$$Y = \Psi_1(X). \qquad (23.23)$$

This is referred to in the following as the *sorption characteristic* of the injector.

23.3.1.3 Allowance for Variation of $Y(X)$ with Temperature

A separate investigation of the influence of temperature on mass transfer in a water/air system within a temperature range of $\vartheta = 17\text{–}45\,^\circ\mathrm{C}$ has shown that the relationship $Y = \mathrm{f}(X)$ makes full allowance for this effect; the Schmidt number $Sc \equiv \nu/\mathbb{D}$ need not, therefore, be used [23.2].

23.3.2 Pressure Drop Characteristic of an Injector

23.3.2.1 Definition of Individual Δp Values

If an injector is positioned just above the floor of a tall treatment tank ("tower") to serve as a gas disperser, it cannot normally function as an ejector. The gas is fed to it via a separate compressor, which has to work against a pressure composed of the hydrostatic pressure of the liquid column, $H\varrho g$, and the gas-side pressure drop Δp of the injector. The adiabatic power P of the compressor is determined from the following relationship:

$$P = \frac{\kappa}{\kappa - 1}\, q p_1 \left[\left(\frac{p_2}{p_1}\right)^{\frac{\kappa-1}{\kappa}} - 1\right] \Big/ \eta_c, \qquad (23.24)$$

with

$\kappa = 1.4,$

and

$$p_2 = \Delta p(q) + H\varrho g + p_1. \qquad (23.25)$$

The efficiency of a compressor is normally taken as $\eta_c = 0.60$.

The injector does, however, have to be supplied – via a liquid pump – with liquid from the treatment tank which, in the form of a propulsion jet, ensures the dispersion of the gas continuum. Therefore, the liquid throughput suffers a pressure loss Δp_L. The pump power P_L is determined as follows:

$$P_L = \Delta p_L q_L / \eta_L, \qquad (23.26)$$

where q_L (in m^3/s) is the liquid throughput and η_L the efficiency of the pump ($\eta_L \simeq 0.75$).

If both powers, P and P_L, needed to achieve a given O_2 uptake, G (in kg/h), are known, the efficiency of the O_2 uptake is given by:

$$E \equiv \frac{G}{P + P_L} \quad \text{(in kg/kWh)}. \qquad (23.27)$$

The efficiency E of the O_2 uptake is the parameter by which the operating conditions of the injectors are optimized.

23.3.2.2 Formulation According to the Theory of Similarity

Fig. 23.1 shows a schematic cross-section through an injector: this comprises the propulsion jet nozzle and the mixing chamber. d and d_1 are the characteristic diameters of the respective parts of the injector at their narrowest points; Δp_L is the pressure drop of the liquid throughput within the propulsion jet nozzle.

If we consider an injector of given geometry, Δp and Δp_L will depend on the characteristic linear dimensions mentioned, the throughputs q and q_L, as well as on the material parameters of the two fluids, with the densities ϱ and ϱ_L and kinematic viscosities ν and ν_L:

$$\Delta p, \Delta p_L = \mathrm{f}(d, d_1;\ \varrho, \varrho_L, \nu, \nu_L;\ q, q_L). \qquad (23.28)$$

By dimensional analysis these two relationships are reduced to:

$$Eu \equiv \frac{\Delta p\, d_1^4}{\varrho q^2} = \mathrm{f}_1\left(\frac{d_1}{d}, \frac{\varrho}{\varrho_L}, \frac{\nu}{\nu_L}, \frac{q_L}{\nu_L d}, \frac{q}{q_L}\right) \qquad (23.29)$$

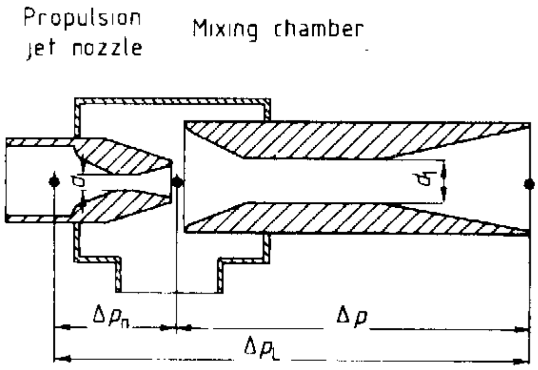

Figure 23.1. Schematic cross-section of an injector showing the pressure drop ranges.

and

$$Eu_L \equiv \frac{\Delta p_L d^4}{\varrho_L q_L^2} = f_2\left(\frac{d_1}{d}, \frac{\varrho}{\varrho_L}, \frac{\nu}{\nu_L}, \frac{q_L}{\nu_L d}, \frac{q}{q_L}\right) \tag{23.30}$$

The Euler numbers Eu and Eu_L depend on only two process numbers: $Re_L \equiv q_L/(\nu_L d)$ and q/q_L, if the material system and geometry are given:

$$Eu = f_1(Re_L, q/q_L), \tag{23.31}$$

$$Eu_L = f_2(Re_L, q/q_L). \tag{23.32}$$

The Euler number Eu_n, which is used in determining Δp_n, is now given by the following relationship:

$$Eu_n = \frac{\Delta p_n d^4}{\varrho_L q_L^2} = Eu_L - \left(\frac{d}{d_1}\right)^4 \frac{\varrho}{\varrho_L} \left(\frac{q}{q_L}\right)^2 Eu \tag{23.33}$$

The determination of the pressure drop characteristics will not be described in more detail since measurement of Δp and Δp_L presents no difficulty. It should be pointed out, however, that for this measurement it is best to position the injector in a bubble column and cover it with a liquid layer of known height, which is then taken into account when the results are analyzed.

23.4 Description of Bayer Injectors [23.1], [23.2]

23.6 Bayer Tower Biology®

23.6.1 Technical Principle

The following process engineering requirements led to the development of the Bayer Tower Biology® principle: The demand for a high efficiency E of the O_2 uptake and for a minimum production of offgas so that thermal treatment of the latter could, where necessary, be carried out economically.

We have already seen from the relationships E_{max}, $x''=f(H)$ for the two injectors described (Figs. 23.12 and 23.13) that, with the usual effluent, a high degree of utilization of atmospheric oxygen under coalescence-promoting conditions can only be achieved with relatively high liquid columns and therefore correspondingly long residence times of the gas bubbles in the liquid. Fig. 23.14 shows clearly that the optimum liquid height, as far as the oxygen uptake efficiency alone is concerned, is about 15 m, the O_2 concentration in the off-gas still amounting to roughly 8% by volume (degree of utilization 62%). Higher levels of oxygen utilization are only possible with even higher water columns; these are then achieved at the price of a slight drop in efficiency. It is also apparent from Fig. 23.14 that a reduction to about 4% by volume of oxygen in the off-gas (O_2 utilization 81%) is not possible with a liquid height of less than 26 m; the efficiency of the O_2 uptake here, however, is still about 3.0 kg/kWh.

The idea for the Bayer Tower Biology® concept [23.8] is to construct the treatment unit (activated sludge tank) in the form of a tall vessel, the oxygen being supplied by means of injectors. There were three important requirements here: the injectors had to be only a relatively short distance (½–1 m) above the bottom, positioned so that they point towards the bottom, and they also had to be equidistant from each other. The aim of the first requirement is to give the gas bubbles the greatest possible vertical distance to travel before they reach the surface; the second is to ensure that there is a vigorous flow of liquid at the bottom of the tank which prevents deposits.

The purpose of the third requirement is to promote the formation of so-called "aeration chimneys" above the injectors to ensure uniform back-mixing over the height of the liquid; this is essential for good O_2 absorption (Δc should be as high as possible and positive throughout).

In the original design, secondary clarifiers (sedimentation funnels or "Dortmund wells") are designed to separate the biomass from the purified waste water. As most of the sedimented biomass is returned to the activated sludge tank ("recycled sludge"), one way of avoiding an increase in the power requirement of the pump was to arrange the sedimentation funnels so that the liquid level in them largely corresponds with that in the main tank. In the case of the Leverkusen Tower Biology, this resulted in a "collar" around the towers, whereas the other Tower Biology units so far constructed have separate secondary clarifiers (sedimentation funnels or „Dortmund wells") at the top of each tower. This concept is illustrated in the sketch in Fig. 23.21.

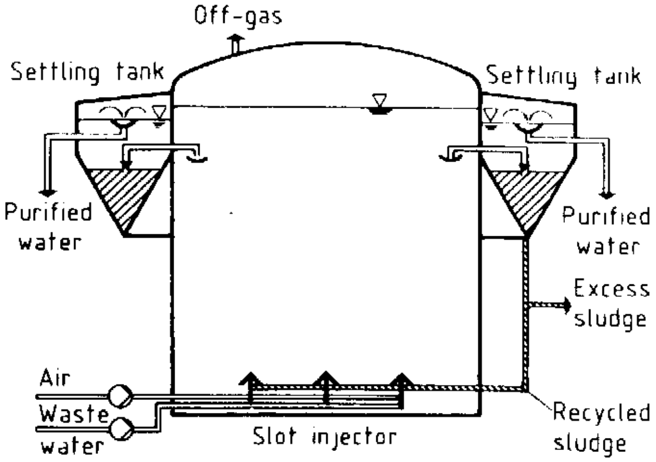

Figure 23.21. Schematic cross section of a Bayer Tower Biology® reactor.

23.6.2 Plants so far Constructed

a) Bayer AG, Leverkusen Works (Germany) [23.9]–[23.11]

The industrial effluent from more than 100 chemical production facilities at Bayer AG's Leverkusen works is conveyed through a double sewer more than 2.5 km long to the "joint sewage treatment plant" in the Leverkusen suburb of Bürrig. A "basin biology" plant with surface aeration has been in operation there since 1971. This first treatment facility built at Bürrig was able to handle part of the industrial effluent from the Bayer factory as well as the municipal sewage from the Wupper water authority area. The Bayer Tower Biology® fa-

Figure 23.22. Photograph of the Tower Biology® plant at Bayer's main factory in Leverkusen, on stream since December 1980.

cilities were erected during the second phase of construction which began in 1976, involving a capital expenditure of DM 135 million. This facility went on stream in December 1980 (cf. Fig. 23.22). Since then it has served as the first stage in the biological treatment of the entire effluent from Bayer's Leverkusen works; the outlet leads to the basin biology, the second stage in biological treatment, which deals not only with the pretreated Bayer effluent but also with the municipal sewage from the Wupper water authority area (dry weather flow).

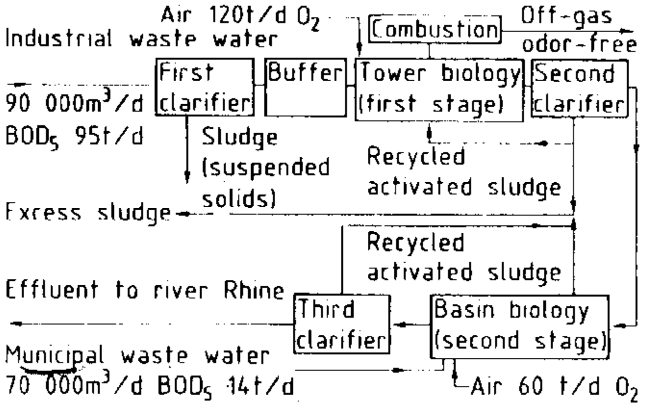

Figure 23.23. Flow diagram of the Leverkusen plant.

The design data for the whole plant (cf. sketch in Fig. 23.23) are:

Intake:

Industrial effluent: 90000 m^3/d with 95t/d BOD_5; plus municipal sewage: 70000 m^3/d with 14 t/d BOD_5.

Primary clarification:

Residence time 2.5 h.

Tower Biology:

4 rubber-lined steel tanks (Ø 26 × 30 m) in parallel; liquid height 26.5 m, tank volume 13600 m^3, total volume 54400 m^3. Aeration via 4×72 slot injectors. O_2 uptake 120 t/d, 22000 m^3/h air (standard conditions) being required for an O_2 utilization of up to $x'' = 4\%$ O_2 by volume. Volume load 1.8 kg/m^3 d BOD_5, sludge load 0.32 kg BOD_5 per kg dry mass per day, residence time 14.5 h.

Off-gas purification:

The off-gas is pre-heated in a countercurrent to about 580°C and mixed with approximately 160 m^3/h of natural gas. "Non-flaming combustion" is induced by infrared radiation. This oxidation takes place in a reaction chamber at 750°C. The flue gas is subsequently cooled in a counter-current heat exchanger to 200 °C, and the HCl resulting from the oxidation of chlorinated hydrocarbons is removed in a dry absorption column (burnt lime, CaO). The spent lime is separated by a filter bag and used afterwards for waste water neutralization. The off-gas purified in this way is discharged into the atmosphere through a short chimney at a temperature of about 180 °C.

Intermediate clarification:

Each tower has a "collar" of 16 sedimentation funnels of 9 m Ø with a total volume of 16 × 420 m³ = 6720 m³ per tower. Residence time 7 h, superficial velocity 0.95 m/h.

Basin biology
(second stage in the biological treatment of Bayer effluent):

2 flat basins in series ($H = 3.5$ m) with respective volumes of 11 500 and 25 000 m³. Residence time 3.4 + 7.5 h, O_2 uptake 60 t/d.

Secondary clarification
(sedimentation of biomass):

Basin with scraper ($\tau = 3$ h) and sedimentation funnels ($\tau = 6.3$ h).

b) Bayer AG, Brunsbüttel Works (West Germany) [23.12], [23.13]

Following several years' experience with the 8 m-high biotanks (Fig. 23.24, foreground), the second phase of construction was completed in 1979. Six tanks then went into operation (Ø 10 × 15 m, volume 1200 m³) having a total volume of 7200 m³; these carry out the biological purification of 5600 m³/d of waste water with a BOD_5 load of 4.2 t/d. This requires an O_2 uptake of 7.2 t/d. The secondary clarifiers (sedimentation funnels) are situated between the towers and are also covered.

c) Bayer Factory at Thane (India)

Tower Biology in concrete towers (2 tanks of Ø 15 × 17 m, water level 15 m) with adjacent sedimentation funnels. Waste wa-

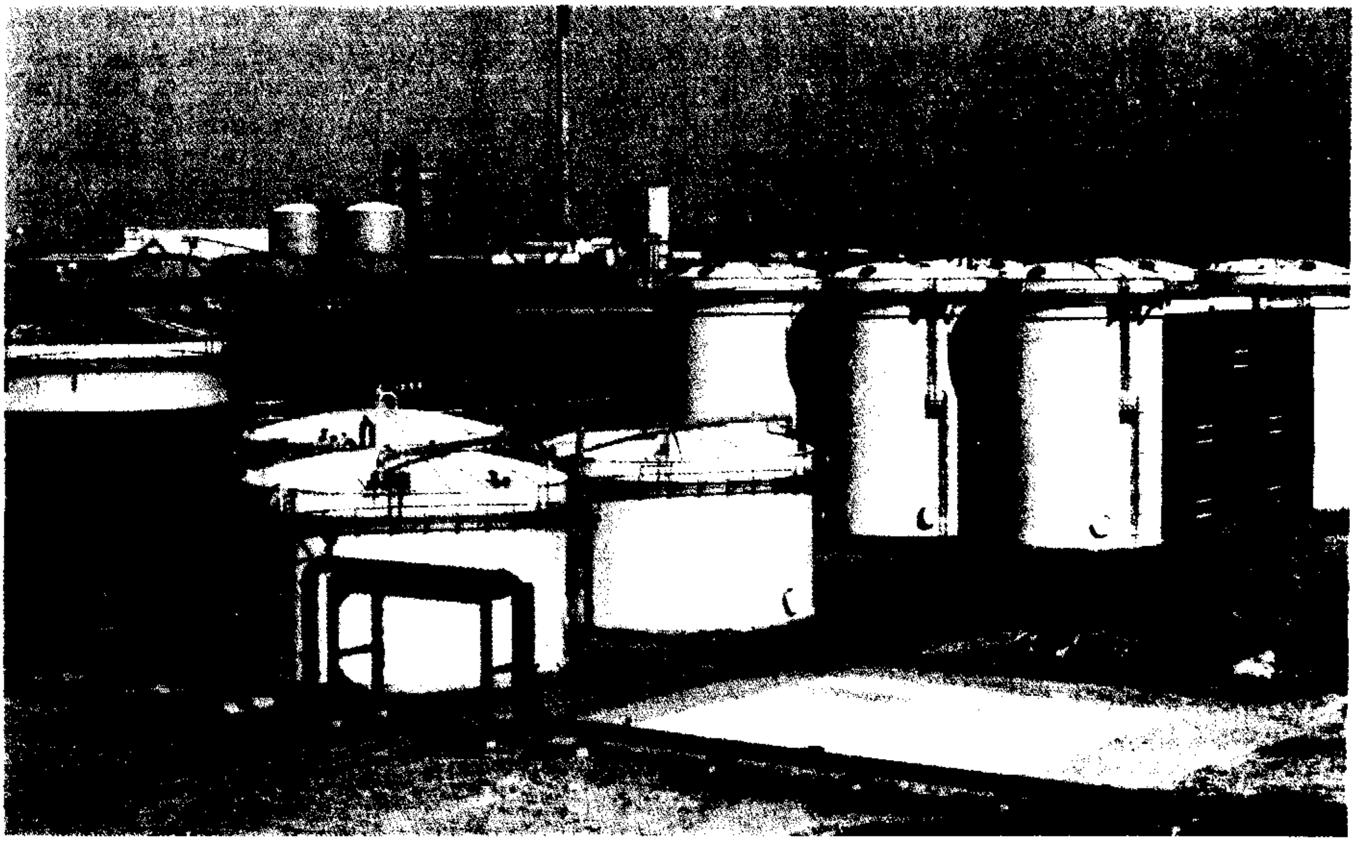

Figure 23.24. Aerial view of the Bayer Tower Biology® reactors (far right) at Bayer's Brunsbüttel works.

ter throughput 3600 m^3/d with a BOD_5 load of 2 t/d; O_2 uptake 4 t/d. This treatment plant commenced operation in 1981.

d) Königsbacher Brewery, Koblenz (West Germany) [23.14] $t_h = \frac{6200}{2000} = 3\,d$

One of the main reasons for the choice of Tower Biology in this case was the lack of space available. The treatment plant consists of a tower (∅ 20 × 20 m) with an adjacent funnel-shaped secondary clarifier. 2000 m^3/d of effluent are treated; the BOD_5 load is 3 t/d. O_2 uptake is 4.2 t/d. The organisms' one-sided diet (carbohydrates) encourages the formation of filamentous activated sludge, which tends to rise to the surface during deaeration of the Tower Biology® outlet. To deal with this, a new type of flotation unit was installed, consisting of a single flotation cell ($D = 2.5$ m; $V = 30\ m^3$) with a funnel-shaped nozzle (induced air flotation) [23.15]. This gives a recycled sludge with about 10 g/L dry matter and a water-clear outflow of the purified waste water. The Tower Biology went on stream in 1981.

6200 m^3

e) Petrochemical Plant in Wesseling, North Rhine-Westphalia (West Germany) [23.16]

Here, there is 8000 m^3 of waste water to be treated daily, containing an ammonium (NH_4^+) load of 8 t/d as well as a BOD_5 load of 6 t/d. Nitrification and denitrification processes therefore have to be integrated into the biological treatment for purposes of nitrogen elimination. Following extensive trials on a semi-technical scale, the industrial-scale plant shown in the sketch in Fig. 23.25 was designed. The plant comprises a two-step nitrification, the first step also incorporating the aerobic oxidation of carbon as well as 70% nitrification (from 800-1000 ppm to 100-150 ppm). In the second step, the remaining NH_4^+ is degraded to 5-30 ppm. The nitrites and nitrates thus formed then have to be reduced to nitrogen with the aid of hydrogen donors (e.g., methanol). To save on methanol, the outflow from the second nitrification step is divided into two streams; 40% of the total is fed to a denitrification unit upstream from the first nitrification unit, and 60% passes to the downstream denitrification unit to which is added an effluent free of N but rich in hydrocarbons (methanol). An activated sludge tank is then required downstream from the denitrification unit to degrade the residual BOD_5 resulting from these additional streams.

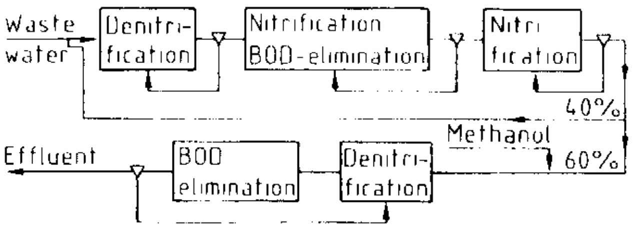

Figure 23.25. Flow diagram of combined BOD elimination and nitrification/denitrification.

Since the nitrification unit has a high O_2 demand (4.57 kg oxygen per kg of ammonia nitrogen), the entire plant was designed in the form of a multi-step Tower Biology; the O_2 uptake is 50 t/d. It comprises seven towers of between 24 and 17 m in height plus six sedimentation funnels, see Fig. 23.26. These commenced operation in July 1981 and have proved entirely satisfactory.

f) Dynamit Nobel, Lülsdorf Works (West Germany) [23.17]

In this case the effluent (15000 m^3/d) carries not only the BOD_5 load (14 t/d) but also the NO_3^- load (3 t/d) from the nitration process. The plant consists of two parallel lines, each containing a denitrification unit (∅ 12 × 22 m; $V = 2500\ m^3$) and an activated sludge unit (∅ 17 × 20 m, $V = 4500\ m^3$). This treatment plant went on stream in July 1983.

g) Lehrter Zucker AG, Lehrte, near Hannover (West Germany) [23.18]

The special feature of sugar factories as far as their effluents are concerned is that effluent only occurs during a particular season (after the sugar beet harvest) and also that it contains a high carbohydrate concentration and is therefore best pretreated in an anaerobic unit. This is also true for Lehrter

Figure 23.26. Bayer Tower Biology® facility at a refinery operating according to the principle illustrated in Fig. 23.25.

$t_R = \frac{3200}{3000} \sim 1\ d$

Zucker AG. Here, only the downstream aerobic treatment unit takes the form of a Tower Biology plant (Ø 15 × 18 m; $V = 3200\ m^3$); the O_2 uptake is 5–7 t/d (max.). This plant handles 3000 m^3 of waste water per day, which contains 7–10 g/L of COD and 4.5–7.2 g/L of BOD_5. The plant went into operation in the autumn of 1982.

h) Bitburger Brewery, Bitburg (West Germany) [23.19]

The excellent results obtained with the combination of Tower Biology and induced air flotation at the Königsbacher brewery in Koblenz prompted the Bitburger brewery to choose the same system. The plant at Bitburg comprises a tower (Ø 20 × 24 m, $V = 7300\ m^3$) and a downstream flotation unit consisting of two parallel flotation cells, each with a volume of 50 m^3. The plant commenced operation in January 1984 and treats 7200 m^3 of effluent daily.

$t_R = \frac{7300}{7200} \sim 1\ d$

23.7 BIOHOCH Reactor® of Hoechst AG[*)]

23.7.1 Process Engineering Concept

The incentive to develop a tower-shaped reactor at Hoechst AG came chiefly from the need to save space and reduce the emission of off-gas. The design of this facility can be seen as a further stage in the devel-

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* This section was kindly contributed by H. G. MÜLLER, Hoechst AG, Frankfurt am Main, Federal Republic of Germany.

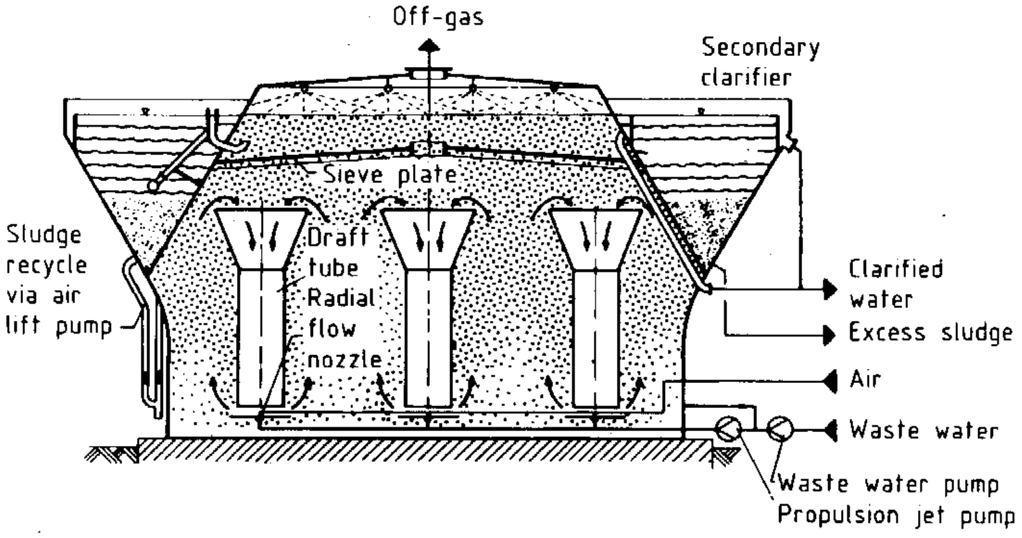

Figure 23.27. BIOHOCH Reactor® of Hoechst AG (multi-loop reactor).

opment that began with the low-level design (1967) with basin depths of 3.5 m, continued with the medium-level unit with water depths of 10 m and finally led to the BIOHOCH reactor [23.20].

The BIOHOCH reactor consists basically of an almost cylindrical activated sludge tank and a conical secondary clarification unit forming a ring around the activated sludge tank, cf. Fig. 23.27. The activated sludge tank is divided by a sieve plate into two chambers. This results in a reduction in the gases (N_2, CO_2) dissolved in the sludge-water mixture in the upper part of the reactor. It improves the settling characteristics of the activated sludge in the secondary clarifier.

The biomass precipitated from the treated waste water flows back from the secondary clarifier into the aeration tank via air lift pumps. The quantity of sludge recycled is controlled by the air fed into the sludge recycle pipe.

In order to improve sludge sedimentation, rotating rakers are installed in the secondary clarifier. The function of the draft tubes installed in parallel in the aeration tank is to improve vertical back-mixing of the activated sludge. The difference in density between the aerated liquid outside the draft tubes and the non-aerated liquid inside gives rise to a strong circulatory current. The water emerges horizontally from the lower end of the draft tubes, thus preventing the deposition of solids on the bottom; the raw sewage added is mixed quickly and evenly with the contents of the reactor.

The activated sludge is aerated by radial flow nozzles on the bottom, through which charging of the reactor with pretreated, neutralized effluent also takes place.

In order to improve the bubble distribution, the radial flow nozzles are arranged beneath the draft tubes.

The operation of a bubble column or loop reactor is chiefly influenced by the arrangement and mode of operation of the aerators. This applies in particular to the large-surface aeration of the activated sludge stage in a waste water treatment plant.

In the technology of waste water treatment, aerators have to meet a number of requirements:

- high oxygen input
- optimum utilization of the oxygen content of the aeration air and thus low off-gas quantities
- thorough back-mixing of the waste-sludge mixture
- noiseless operation
- reliability of operation, in particular freedom from clogging.

On the basis of these criteria, a wide variety of aeration systems were examined, the most favorable results being obtained with the two-phase nozzles [23.21], [23.22]. With these nozzles, the air is dispersed by the kinetic energy of a water jet (propulsion jet).

23.7.2 Radial Flow Nozzle

Extensive tests resulted in the development of the radial flow nozzle, Fig. 23.28. With this nozzle, the propulsion jet is converted with the aid of a deflecting element into a radially spreading fan jet. The air is introduced into the liquid through an annular slot behind the deflecting element [23.23]. The gas distributor plate prevents rapid rising of the bubbles.

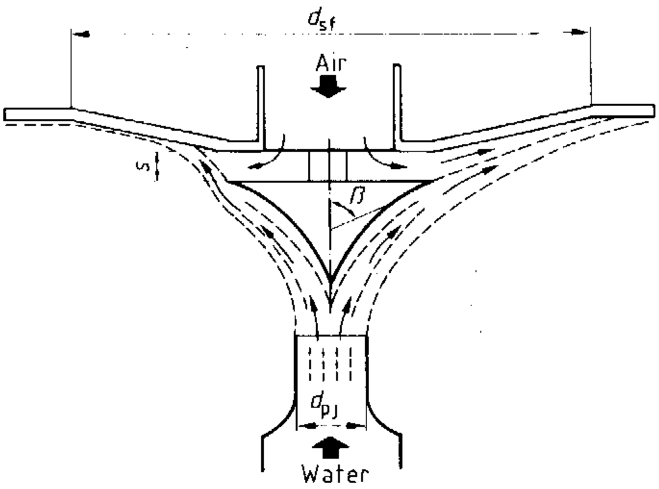

Figure 23.28. Radial flow nozzle. d_{sf} shear field diameter, d_{pj} propulsion diameter, β angle of deflecting cone, s slot width.

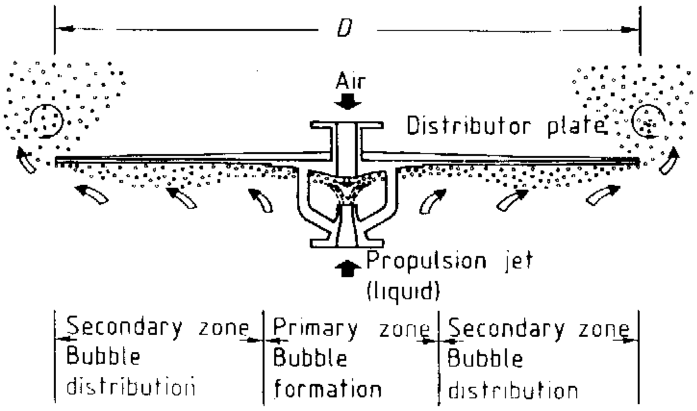

Figure 23.29. Bubble formation and bubble distribution using a radial flow nozzle.

The turbulent flow of the bubble/water mixture is compelled to flow radially outwards and to mix with the secondary water drawn in. The gas content declines with increasing distance from the bubble formation zone, thus reducing bubble coalescence. A vortex of gas bubbles forms above the distributor plate. Fig. 23.29 shows this nozzle in cross-section.

The re-shaping of the propulsion jet to form a fan means that when the jet diameter is increased, the shearing area and the cross-sectional area of the jet both increase with the square of the jet diameter. The geometric parameters such as the deflection angle, the diameter or the gap width s have in this respect a considerable influence on bubble formation.

The radial flow nozzles are made from ordinary steel or high-grade steel, the plug, which is subject to high stress, is made from a special alloy (see Fig. 23.30). Fig. 23.31 shows the bubble pattern of a radial flow nozzle.

Tests performed with model nozzles in smaller units by means of fixed measuring devices employing the hydrazine method or sulfide oxidation method yielded no significant, utilizable results. No more meaningful information was obtained when using the mobile input tests commonly employed in waste water treatment technology. They were not suitable as a basis for designing the aeration system of the BIOHOCH reactor®.

With all these methods it is assumed that in the volume examined, the oxygen transfer rate coefficient k_La is constant.

However, this does not apply to aeration tanks with high water levels. In this case, both the k_La value and the concentration difference are locally dependent values.

An additional factor is that the coalescence conditions present in the waste water are completely different from those in a test solution, for example. Studies have shown that the oxygen transfer factor α, which represents the ratio of oxygen uptake in the waste water to oxygen uptake in the treated effluent, does not only depend on the quality of the waste water, but also on geometric and hydraulic parameters, cf. Sect. 23.5.3.

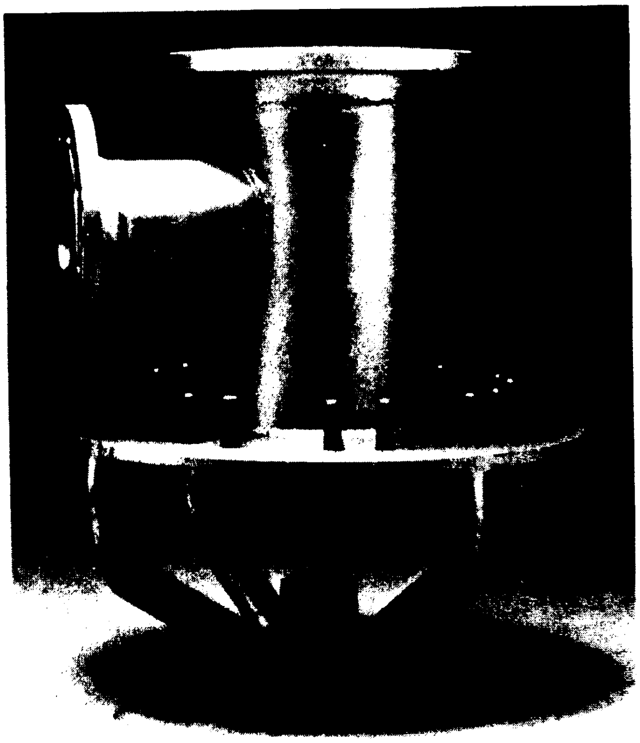

Figure 23.30. Radial flow nozzle with 50 mm propulsion jet diameter.

Figure 23.31. Bubble pattern of a radial flow nozzle.

In order to obtain the most realistic results possible, the nozzles were tested solely in waste water/sludge suspensions. The radial flow nozzles used were of the same design as those later employed in industrial scale plants. The test column was 18 m high and 5 m in diameter.

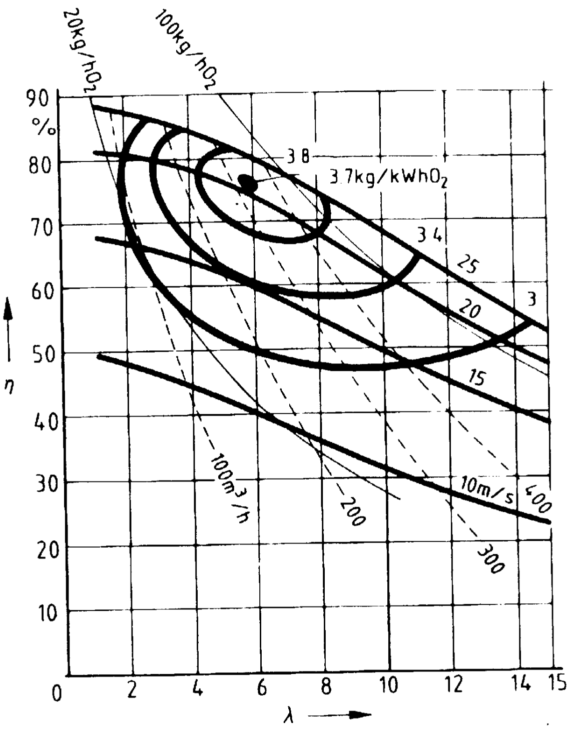

Figure 23.32. Working diagram for a radial flow nozzle (type 30/1500) for coalescence conditions $m = 0.9–1.6$ and standard conditions ($c = 0$ mg/L O_2). λ air/water ratio (m^3 air per m^3 water), η oxygen utilization (%), $H = 17.5$ m.

For the purpose of determining the degree of oxygen utilization, the amount of air and off-gas was established, as well as the oxygen concentration in the water and off-gas. Oxygen uptake was obtained from the mass balance, as were also the values for degree of oxygen utilization and efficiency.

The various operating states (water and air throughput etc.) and the corresponding efficiency values can be jointly represented by means of characteristic curves, an example of which is shown in Fig. 23.32 for a nozzle with 32 mm diameter at a water level of 17.5 m [23.24].

The optimum condition under which this nozzle achieves its maximum efficiency is a propulsion jet velocity of 21 m/s and an air/water ratio of $\lambda = 6$ (m^3 air per m^3 water). At this point the data are as follows:

Degree of oxygen utilization $\eta = 76\%$

Efficiency	$E = 3.8$ kg/kWh
Oxygen uptake	$G = 72$ kg/h
Air throughput (standard conditions)	$q = 320\ \mathrm{m^3/h}$
O_2 concentration in the off-gas	$x'' = 5\%$ by volume

In order to be able to apply the results to industrial scale plants – e.g., for the purpose of arranging the radial flow nozzles in the BIOHOCH reactor® – it was necessary to obtain an insight into the local mass transfer. The oxygen concentration profiles were therefore determined as a function of height and diameter. During the test, the oxygen concentrations were measured simultaneously in the liquid and gas phase by means of adjustable probes.

In Fig. 23.33 the oxygen concentration is plotted against the liquid height. The left-hand curve shows the oxygen concentration in the ambient liquid, the right-hand curve the oxygen concentration in the liquid at the phase boundary of the air bubbles. The velocity of the propulsion jet in these experiments was 19 m/s.

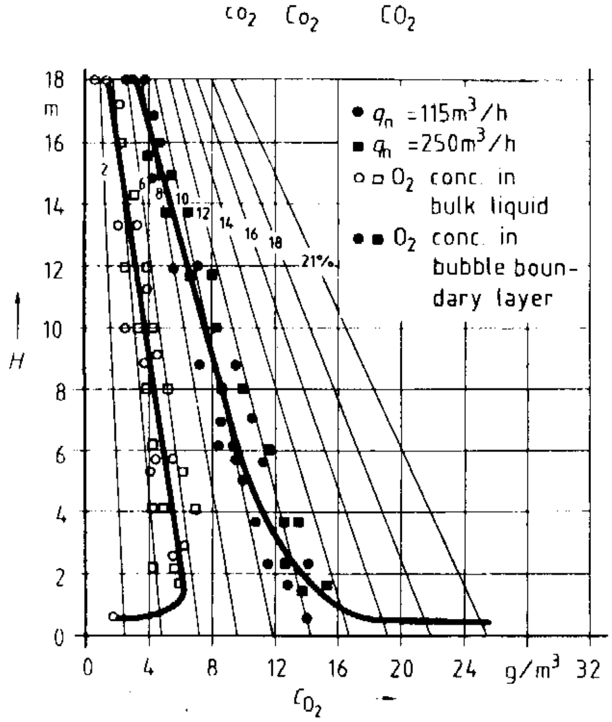

Figure 23.33. Oxygen concentration profile in waste water (type 30/1500). $m = 0.9$–1.4; propulsion velocity $v = 19$ m/s.

From the oxygen profiles the local mass transfer rate coefficients were determined. These values are plotted in Fig. 23.34 against liquid height H. In the lower section, in the area of activity of the nozzles, k_La values were obtained, which after a few meters dropped to the levels associated with bubble columns [23.25], [23.26], [23.27].

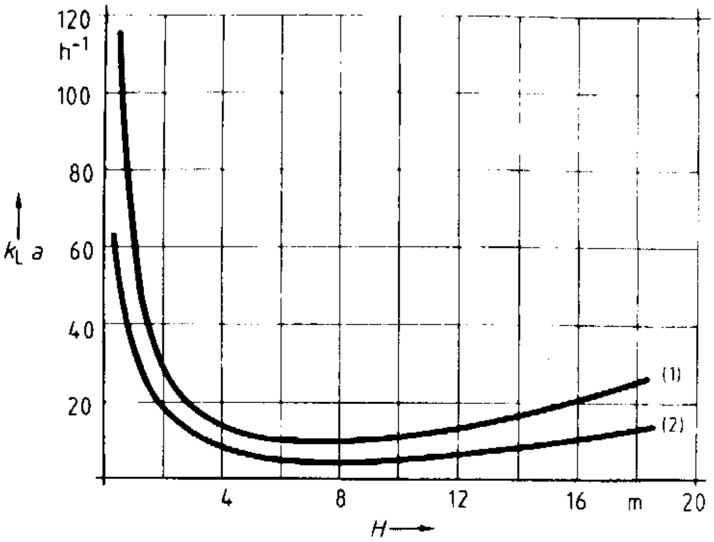

Figure 23.34. Mass transfer rate coefficient k_La as a function of height (type 30/1500). – Waste water $\alpha = 0.6$–1.2, propulsion velocity $v = 19$ m/s, (1) $q_n = 250\ \mathrm{m^3/h}$, (2) $q_n = 115\ \mathrm{m^3/h}$.

Radial flow nozzles with propulsion jet diameters of 30–70 mm are in operation in a number of waste water treatment plants within the Hoechst group and elsewhere. Studies carried out at plants in operation have fully confirmed the test results.

23.7.3 Survey of Plants Already Completed or Under Construction

a) Hoechst AG, Kelheim (Donau) Works (West Germany)

Kelheim is the site of the first of a number of BIOHOCH reactors that have been

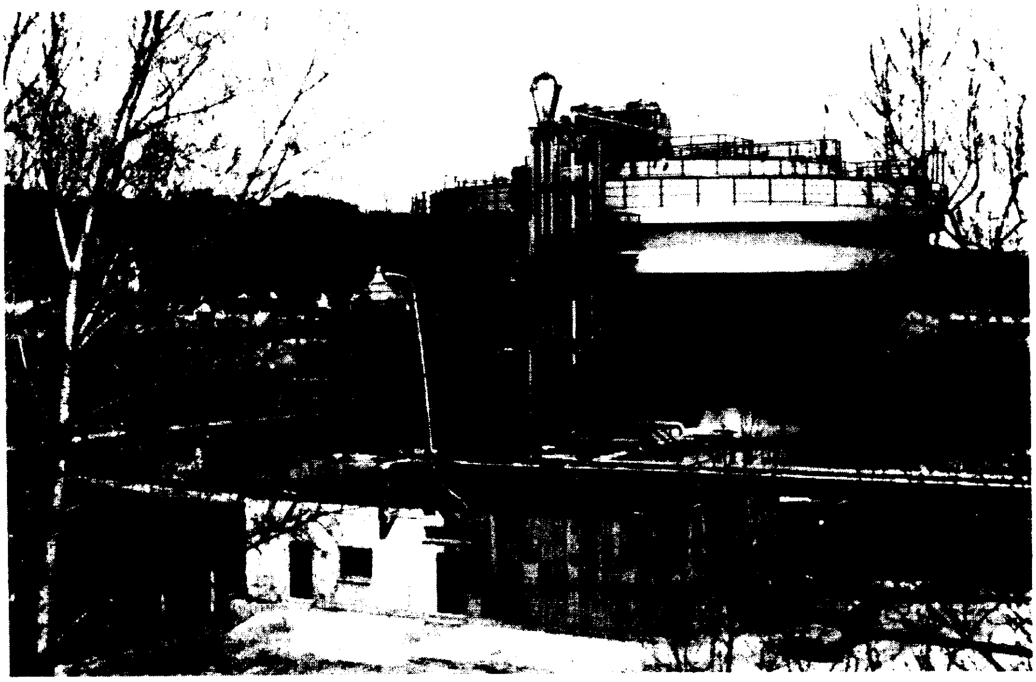

Figure 23.35. Photograph of the BIOHOCH Reactor® at the Kelheim works of Hoechst AG.

built. It has been in operation since October 1981 (Fig. 23.35).

The reactor has a liquid height of 15 m and an activated sludge volume of 3000 m^2; its diameter is 16–24 m.

In the activated sludge tank, seven radial flow nozzles are installed beneath the draft tubes. The propulsion jet is 30 mm in diameter. At a degradation capacity of 8 t/d COD, the BOD_5 concentration averages 16.5 mg/L. 65–85% oxygen utilization is achieved (O_2 concentration in the off-gas 3–7%).

b) Hoechst AG, Griesheim Works (West Germany)

The special feature of the Griesheim effluent is its high content of substances formed during the manufacture of basic products and intermediates for dyes, pharmaceuticals etc., some of which have low degradability or inhibit degradation. In order to improve the degradation efficiency, a modified aeration process is used, the special feature of which is the addition of activated carbon in powder form to the activated sludge. The plant was started up in 1983 (Fig. 23.36).

2 BIOHOCH reactors (steel tanks)

diameter	23–45 m
liquid height	20 m
aerated liquid volume	8000 m^3 per reactor
oxygen utilization	approx. 60–70%
waste water throughput	60000 m^3/d
treatment capacity	15000 kg/d BOD_5
air throughput	3000–10800 m^3/h

c) Cassella AG/Hoechst AG, Offenbach Works (West Germany)

Space saving was the decisive reason for building this joint plant. The mechanically and chemically pretreated effluent from the Offenbach works passes through a pipeline some 3 km in length to the treatment plant, where it is mixed with the pretreated effluent from Cassella AG immediately prior to the activated sludge stage.

Design data for the activated sludge unit:

2 BIOHOCH reactors (with integrated secondary clarification)
steel tanks (epoxy resin coating)

diameter	20–39 m
liquid height	20 m

Figure 23.36. Photograph of the BIOHOCH Reactor® to be used at the Griesheim works of Hoechst AG.

aerated liquid volume	6000 m^3 per reactor
treatment capacity	24000 kg/d BOD_5
air input (standard conditions)	3000–10800 m^3/h

d) Hoechst AG, Hoechst Works (West Germany) (treatment plant under construction)

The treatment capacity of the central waste water treatment plant had to be increased due to rising organic load in the effluent and the desire for more efficient degradation. The capacity of the three parallel waste water treatment units will then be 160000 kg/d BOD_5.

The design data for the 3rd unit are as follows:

2 BIOHOCH reactors
steel tanks/epoxy resin coating

diameter	32.1–45.5 m
liquid height	20 m
aerated liquid volume	15000 m^3 per reactor
treatment capacity	60 t/d BOD_5
air input (standard conditions)	6000–21600 m^3/h

e) E. Merck, Darmstadt (West Germany)

The waste water treatment plant at the Darmstadt works of E. Merck is being enlarged in order to handle the biological treatment of industrial effluent.

The design data for two BIOHOCH reactors were determined by Merck in the course of long-term trials under operating conditions in a pilot plant.

The experimental data obtained led to the construction of *one* large-scale unit, which came on stream in 1983.

Design data:
1 BIOHOCH reactor (steel tanks/rubber lined)

diameter	18.8–33.4 m
liquid height	18 m
aerated liquid volume	5000 m^3
air input (standard conditions)	3500–8000 m^3/h
oxygen utilization	60–70%
maximum COD load	30000 kg/d

f) American Hoechst Corp., Baton Rouge Works (USA)

The waste water treatment plant at the Baton Rouge works went on stream in mid-

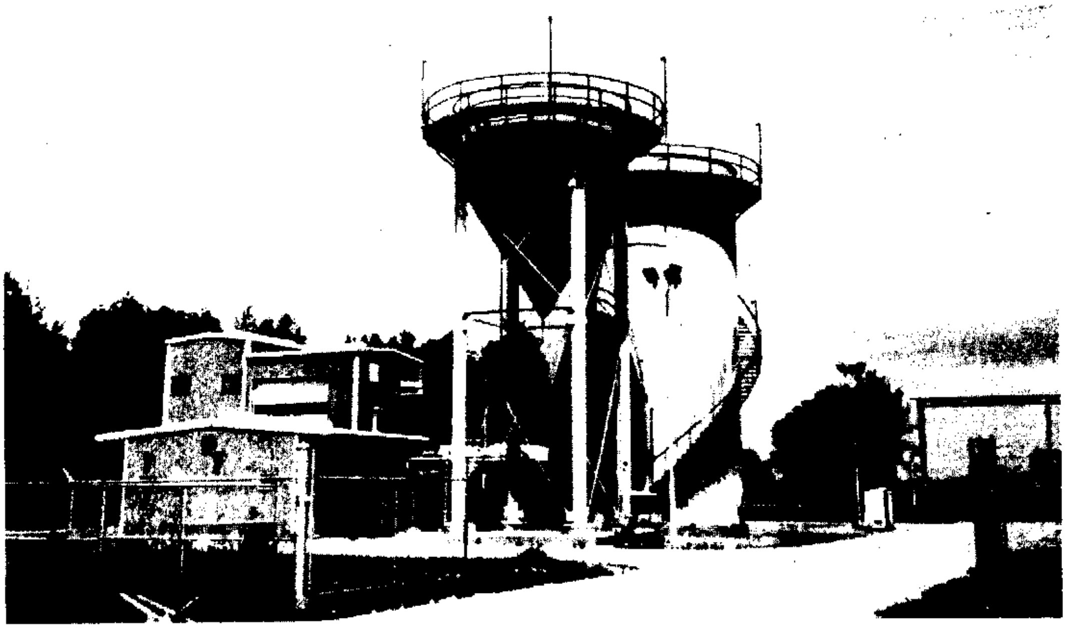

Figure 23.37. Photograph of the BIOHOCH Reactor® at the Baton Rouge works of the American Hoechst Corporation.

April 1983. Here, the BIOHOCH reactor principle is employed in a modified form. The activated sludge tank – a cylindrical vessel – is installed separately from the secondary clarifier – a Dortmund tank. A draft tube is installed inside the tank. The aeration system comprises a radial flow nozzle RS 50/3500*), a propulsion jet pump and a screw compressor unit. The air volume is max. 560 m^3/h. The surface of the water in the activated sludge tank is sprayed with an antifoam.

The design data are as follows:

diameter/height	8 m/14 m
water volume	240–320 m^3/d
treatment capacity	1500 kg/d BOD

Fig. 23.37 shows an over-all view of the plant.

g) Riedel de Haen, Seelze (West Germany)

At Riedel de Haen, the biological waste water treatment plant has been enlarged by a second unit, which went into operation in the spring of 1983. The plant was built for the biological treatment of industrial effluent from the batchwise production of laboratory chemicals. The activated sludge tank, made of concrete, has a diameter of 20 m and a liquid height of 8.75 m. The activated sludge volume is approx. 2700 m^3.

Radial flow nozzles are used for aeration of the tank.

Design data:

waste water throughput	200 m^3/h
oxygen uptake	approx. 250 kg/h
air input (standard conditions)	3300 m^3/h
oxygen utilization	40%–50%

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[*] 50 mm diameter of the propulsion jet nozzle, 3500 mm diameter of the distribution plate

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