Transfer number in fine bubble diffused aeration systems

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Abstract On the basis of full-scale data from 58 clean water tests performed in 26 activated sludge tanks equipped with fine bubble diffusers and of a theoretical approach, it can be stated that fine bubble aeration systems with total floor coverage arrangement provide higher kLa values and the lowest spiral liquid circulation.

An efficiency criterion for oxygen transfer (N_T) was defined on the basis of the dimensional analysis. The transfer number N_T allows us to take account of the impact of vertical liquid circulation movements on oxygen transfer. The values of N_T calculated from the results of full scale nonsteady-state clean water tests vary from 5.3×10^{-5} to 9.1×10^{-5} and are directly dependent upon the arrangement of air diffusers. It has been shown that the highest transfer numbers corresponded to the total floor coverage arrangement and the average calculated N_T values is 7.7×10^{-5}, independently of the diffuser density and of the gas velocity, over the ranges studied. The lowest transfer numbers are obtained when the diffusers are located in separate grids, and the transfer number is reduced with increasing air flow rate.

Keywords Clean water tests; fine bubble aeration; oxygen transfer

Nomenclature

a = specific interfacial area ($m^2.m^{-3}$)
d_B = diameter of air bubbles (m)
DD = diffuser density (%)
D_{O2} = coefficient of oxygen molecular diffusion ($m^2.s^{-1}$)
g = acceleration of gravity ($m.s^{-2}$)
G = gas-liquid slip velocity ($m.s^{-1}$)
H_{imm} = depth of submergence of diffusers (m)
k_L = oxygen transfer coefficient ($m.s^{-1}$)
k_La = volumetric oxygen transfer coefficient (h^{-1})
N_T = transfer number (–)
t_c = contact time of the bubble in the liquid (s)
U_G = superficial gas velocity ($m.s^{-1}$)
U_L = superficial liquid velocity ($m.s^{-1}$)
U_t = terminal rise velocity ($m.s^{-1}$)

Greek letters

ε_G = gas holdup (–)
ε_L = liquid holdup (–)
μ = dynamic viscosity of the liquid ($kg.m^{-1}.s^{-1}$)
ρ = liquid density ($kg.m^{-3}$)
σ = surface tension of the liquid ($dyne.cm^{-1}$)

Introduction

Oxygen transfer in aeration basins is generally characterised by the volumetric oxygen transfer coefficient (k_La). In the case of fine bubble diffused air systems, the main parameters influencing k_La in clean water are the air flow rate (Déronzier *et al.*, 1998; Gillot and Héduit, 1998; Wagner and Pöpel, 1998), the arrangement and density of air diffusers (ASCE, 1994; Wagner and Pöpel, 1998) and the depth of submergence of the diffusers (Jackson and Shen, 1978; Khudenko, 1986; Pöpel and Wagner, 1994).

The effect of these parameters on oxygen transfer, by modifying the bubble size, the hydrodynamics and/or the contact time of the bubbles in the liquid, varies from one site to another. To compare the performance of different systems or to transpose results from one scale to another, dimensional analysis is commonly used (Khudenko, 1986; Fujie, 1997). Two systems characterised by the same dimensionless variables are said to be similar and present the same level of performance (Zlokarnik, 1998).

The purpose of this paper is to define, using dimensional analysis, an oxygen transfer efficiency criterion in fine bubble diffused air systems and to examine its capacity for assessing the impact of the arrangement of diffusers on oxygen transfer. The effect of diffuser density and variations in the air flow rate is also examined.

Theoretical approach

Volumetric oxygen transfer coefficient [k_La] in clean water

The volumetric oxygen transfer coefficient [k_La] is defined as the product of the oxygen transfer coefficient [k_L] and the specific interfacial area [a].

The oxygen transfer coefficient. [k_L] depends on the size of the bubbles (d_B), on the terminal rise velocity (U_t), on temperature (T) and on the characteristics of the liquid (σ, μ, ρ) : $k_L = f(d_B, U_t, T, \sigma, \mu, \rho\ldots)$.

For bubble diameters of more than 2.5 mm, k_L can be determined from Higbie's penetration model (1935) :

$$k_L = 2\sqrt{\frac{D_{O2}}{\pi t_c}} = 1.13\sqrt{\frac{D_{O2}}{t_c}} \quad \text{with } t_c = \frac{d_B}{U_t} \tag{1}$$

For bubble diameters in the range of 3 and 4 mm (produced by fine bubble diffused air systems), the terminal rise velocity (U_t) remains constant at 0.24 $m.s^{-1}$ in clean water (Stenstrom and Gilbert, 1981). For a given temperature, k_L can also be expressed as : $k_L = f(d_B)$.

The specific interfacial area [a] depends on the gas holdup and on the bubble size :

$$a = \frac{6}{d_B}\frac{\varepsilon_G}{1-\varepsilon_G} \tag{2}$$

The gas holdup, defined as the air content in the water, can be determined using the slip model of Wallis (1969) :

$$= \frac{U_G}{\varepsilon_G} - \frac{U_L}{\varepsilon_L} \tag{3}$$

nd

$$\varepsilon_G + \varepsilon_L = 1 \tag{4}$$

U_G and U_L are the superficial gas and liquid velocities co-currently in a bubble column.

By combining the Eqs. (3) and (4), the gas holdup is written as follows :

$$\varepsilon_G = \frac{(U_G + U_L + G) \pm \sqrt{(U_G + U_L + G)^2 - 4U_GG}}{2G} \tag{5}$$

The gas-liquid slip velocity (G) can be assimilated to the terminal rise velocity : $G \approx U_t$ (Shal *et al.*, 1982). This is written : $a = f(d_B, U_G, U_L)$.

The volumetric oxygen transfer coefficient k_La. By combining the Eqs. (1), (2) and (5), k_La can be estimated from the following equation :

$$k_La_T = 1.13\sqrt{\frac{D_{O_2}U_t}{d_B}}\cdot\frac{6}{d_B}\cdot\frac{(U_G+U_L+G)\pm\sqrt{(U_G+U_L+G)^2-4U_GG}}{(-U_G-U_L+G)\mp\sqrt{(U_G+U_L+G)^2-4U_GG}} \qquad (6)$$

Parameters influencing oxygen transfer in clean water

The theoretical approach above (Eq. (6)) makes it possible to calculate the volumetric oxygen transfer coefficient k_La in clean water, taking account of the main parameters involved: $k_La = f(d_B, U_L, U_G)$.

In clean water, the *bubble size* (d_B) which essentially depends on the type of diffuser and on the pore size (Da Silva-Déronzier, 1994; Hébrard, 1995) determines the surface area (cf. Eq. 2).

The *superficial liquid velocity* (U_L) is generated by the air-lift action of the air bubbles rising in the liquid. U_L depends essentially on the diffuser arrangement (Fujie, 1997). When the diffusers are arranged in a grid occupying only a part of the bottom of the basin (Figure 1a), the liquid driven by the bubbles preferentially moves to those parts of the basin devoid of diffusers, thus creating a rotation of the liquid, increasing the rise velocity of the bubbles and reducing their contact time in the liquid. On the other hand, when the diffusers are uniformly arranged on the floor of the basin (Figure 1b), the liquid circulation movements are smaller and the liquid velocity distinctly reduced.

Figure 2 presents (dotted lines), for a bubble diameter set at 3.5 mm (mean diameter generated by fine bubble systems), the influence of the *gas velocity* U_G on the volumetric oxygen transfer coefficient k_La for different vertical velocities of the liquid U_L, according to the Eq. (6).

For a constant liquid velocity (UL), the volumetric oxygen transfer coefficient k_La is an increasing function of the gas velocity. It can also be seen that at a given gas velocity a reduction of k_La by approximately 50% can be expected when the vertical component of the liquid velocity rises from 0 to 0.20 m.s^{-1}.

Dimensional analysis

Previous studies based on the theory of similarity have evidenced that a dimensionless number, characteristic of the oxygen transfer, can be defined : the transfer number (N_T) (Zlokarnik, 1978; Roustan, 1996) :

$$N_T = \frac{k_La}{U_G}\left(\frac{\mu^2}{\rho^2 g}\right)^{1/3} \qquad (7)$$

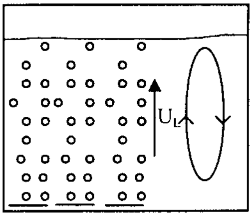

Figure 1a Diffusers arranged in grids

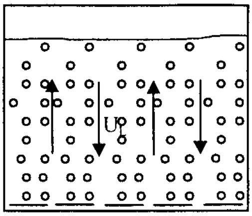

Figure 1b Total floor coverage arrangement

The transfer number N_T characterises the oxygen transfer efficiency of an air diffused system. To within the acceleration of gravity (g) and the characteristics of the liquid (μ, ρ), the transfer number relates the same physical significance as the oxygen transfer efficiency per metre of immersion.

According to the theoretical approach above, N_T can be written : $N_T=f(U_G, U_L, d_B)$. Assuming that fine bubble diffused air systems (discs or tubes) produce bubbles of the same size, the transfer number essentially becomes a function of the gas and liquid velocities : $N_T=f(U_G, U_L)$.

Materials and method

The results of 58 measurements of oxygen transfer efficiency in clean water carried out over the last decade by the Cemagref in 26 basins of different geometry and volume (water depth under 7 m) are given in Appendix I. These data focus solely on fine bubble diffused air systems (discs or tubes) without any horizontal liquid velocity induced by a mechanical agitation. The oxygen transfer coefficients were measured in clean water according to the nonsteady-state method (Héduit and Racault, 1983; ASCE, 1992; Duchène *et al.*, 1995; ATV, 1996).

The diffuser density is expressed as the ratio between the total (perforated) area of the membranes and the total surface area of the oxidation tank. The gas velocity is defined as the air flow rate divided by the surface area of the basin, the air flow rate being expressed at a temperature of 0°C and a pressure at mid-height of (1013+ΔP/2)hPa (where ΔP is the hydrostatic pressure). The transfer number is calculated from the volumetric oxygen transfer coefficients measured, from the gas velocity and from the dynamic viscosity of clean water, according to Eq. (7).

The transfer number was calculated for each site tested and its capacity to take account of the impact of the liquid circulation movements created by the arrangement and density of the diffusers and the variations in air flow was examined.

Results and discussion

Volumetric oxygen transfer coefficient k_La

Figure 2 shows all the experimental volumetric oxygen transfer coefficients and the theoretical curves (dotted lines) of k_La taken from Eq. (6) as a function of U_G and U_L.

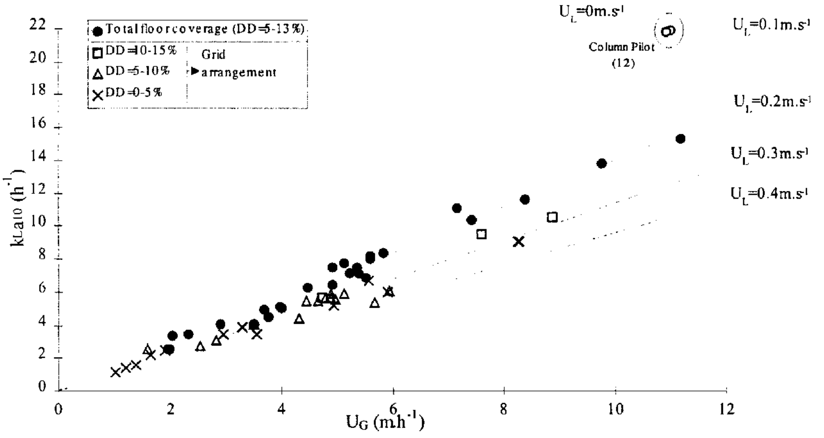

Figure 2 Influence of the gas and liquid superficial velocities on the volumetric oxygen transfer coefficient at 10°C from different full-scale clean water aeration tests

All the experimental data are characterised by a theoretical liquid velocity ranged from 0.1 to 0.4 m.s^{-1}.

The total floor coverage arrangement corresponds to the highest k_La values and to the lowest circulation velocities ($U_L \approx 0.15$ to 0.25 m.s^{-1}), irrespective of the gas velocities and of the diffuser density.

When the diffusers are arranged in separate grids, the liquid circulation velocities are higher (between 0.25 and 0.4 m.s^{-1}), especially when the diffuser density is below 10%.

The pilot installation (site 12) is characterised by a higher k_La value, explained by a high diffuser density (35%) and a low liquid velocity (below 0.1 m.s^{-1}).

The transfer number (N_T)

Irrespective of the basin geometry (cylinder, channel, parallelepiped) and the volume of liquid (from 18 m^3 to 5000 m^3), the transfer number in full scale plants is ranged between 5.3×10^{-5} to 9.1×10^{-5} (cf. Appendix I).

The pilot installation (site 12) is characterised by high transfer numbers (11×10^{-5}), which evidences that the hydrodynamics of this system are not comparable to those of full-size aeration tanks and that any extrapolation of the results obtained in the pilot to the performance to be expected at full-scale plants must be considered with circumspection.

Figure 3 shows the influence of the diffuser layout on the transfer number N_T, for a diffuser density comprised between 7 and 10% and a gas velocity of approximately 5 m.h^{-1}.

The transfer number is on average 7.8×10^{-5} when the diffusers are located uniformly on the bottom of the tank and between 6.4×10^{-5} and 6.6×10^{-5} when the diffusers are arranged in separate grids.

The transfer number N_T thus allows us to translate the influence of the *arrangement* of the diffusers on the transfer efficiency through the vertical liquid velocity UL induced between the grids of diffusers.

Full-floor coverage systems. The highest transfer numbers (cf. Appendix I) correspond to the total floor coverage arrangement tested : the average of the 26 values calculated is $N_T = 7.7\times10^{-5}$ (n=26, standard deviation=0.6), with only two N_T values under 7.0×10^{-5}.

Over the ranges studied, the effect of an increase in gas velocity and of a variation in diffuser density on the transfer number is not noticeable (cf. Appendix I).

The liquid circulation movements generated in this configuration occur between the diffusers and result therefore in low vertical liquid velocities, having little effect on the transfer number.

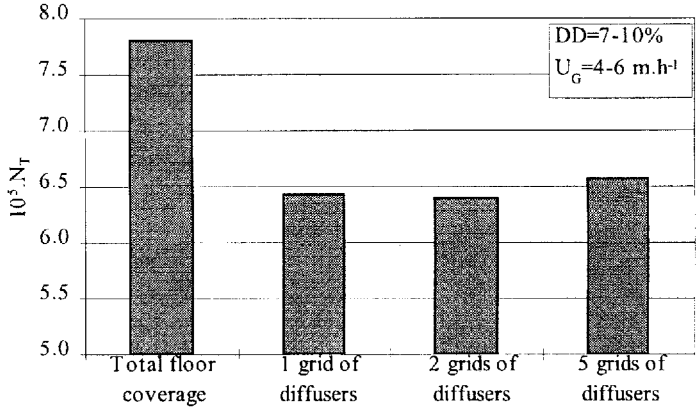

Figure 3 Influence of the diffuser layout on the transfer number (Site no.1, 3, 8, 9, 14, 24, 25 and 26)

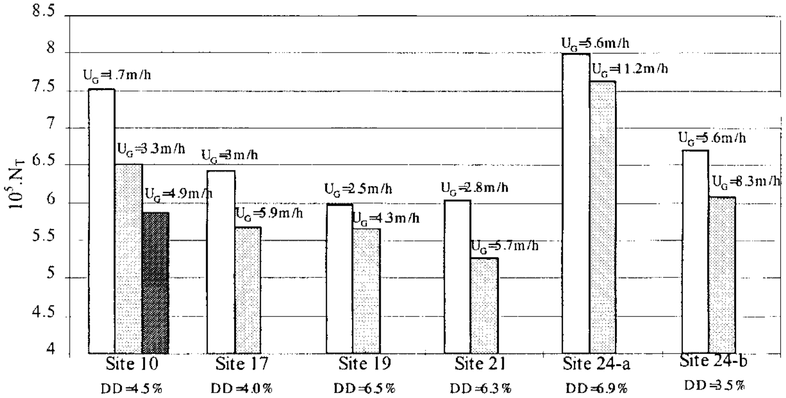

Figure 4 Influence of the gas velocity on the transfer number (grid arrangement)

Basins with separate grids of diffusers. The average of the transfer numbers when the diffusers are located in separate grids is lower than that of the transfer numbers for basins with a total floor coverage arrangement : $N_T = 6.4\times10^{-5}$ (n=30, standard deviation=0.7).

As for full-floor coverage systems, variations in the diffuser density over a range from 3% to 15% do not appear to influence the transfer number (cf. Appendix I).

On the other hand, Figure 4 shows the effect of an increase in the gas velocity on the transfer number for 5 different wastewater treatment plants, where the diffusers are arranged in separate grids (diffuser density between 3.5% and 7%).

An increase in the air flow rate per surface area unit of the basin results in a decrease of N_T.

The influence of variations in the air flow rate on the transfer number N_T is thus more noticeable when the grids of diffusers are spaced out, namely when the liquid circulation rates occur between the grids are the greatest (see Figure 4), than in full-floor coverage systems where the vertical liquid velocities are induced between the diffusers.

Conclusions

The volumetric global oxygen transfer coefficients $[k_La]$ determined in 58 clean water tests were depicted according to the gas velocity measurement and the vertical liquid velocity, determined by a theoretical approach.

This evidenced that the highest $[k_La]$ values, and the lowest vertical liquid circulation velocities are found for full-floor coverage systems, irrespective of the gas velocity and diffuser density.

The dimensional analysis allowed to define a dimensionless number, characteristic of the oxygen transfer. This efficiency criterion, written as N_T, is expressed according to the volumetric oxygen transfer coefficient, the gas velocity and the liquid characteristics (ρ, μ).

The experimental values of N_T were then calculated from the results of clean water tests. The values of N_T vary from 5.3×10^{-5} to 9.1×10^{-5} and are directly dependent on the arrangement of the diffusers.

- The highest transfer numbers ($N_T=7.7\times10^{-5}$, n=26, standard deviation=0.6) correspond to total floor coverage arrangements of diffusers (low vertical liquid circulation between the diffusers).
- Smaller transfer numbers ($N_T=6.4\times10^{-5}$, n=30, standard deviation=0.7) are obtained when the diffusers are located in separate grids (high vertical liquid circulation between the grids of diffusers).

- Over the range studied, the diffuser density, irrespective of the diffuser layout, has little influence on the transfer number (3% to 15%).
- When the diffusers are located in separate grids, an increase in the air flow rate, amplifying the liquid movements between the grids of diffusers, results in a drop in the transfer number.

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References

ASCE (1992). ASCE Standard measurement of oxygen transfer in clean water. *American Society of Civil Engineers*.

ASCE (1994). Manual of Practice. *FD-13 (WPCF)*.

ATV (1996). Messung des Sauerstoffzufuhr von Belüftungseinrichtungen in Belebungsanlagen in Reinwasser und in belebtem Schlamm.

Da Silva-Déronzier, G. (1994). *Eléments d'optimisation du transfert d'oxygène par fines bulles et agitateur séparé en chenal d'épuration.* Thèse de doctorat en Génie de l'environnement. Université Louis Pasteur, Strasbourg 126 p + annexes.

Déronzier, G., Duchène, Ph. and Héduit, A. (1998). Optimization of oxygen transfer in clean water by fine bubble diffused air system and separate mixing in aeration ditches. *Wat. Sci. Tech.*, **38**(3), 35–42.

Duchène, P., Schetrite, S., Heduit, A. and Racault, Y. (1995). Comment réussir un essai d'aérateur en eau propre. Cemagref Editions. *Gestion des Milieux Aquatiques, Etude 9*, 36 p.+annexes.

Fujie, K., Kasakura, T., Tsuchiya, K. and Tomita, Y. (1997). Effects of air diffuser arrangement on hydrodynamics and oxygen transfer in activated sludge aeration tanks. *Environ. Tech.*, **18**, 663–668.

Gillot, S. and Héduit, A. (1998). Effect of air flow rate on oxygen transfer in activated sludge in an oxidation ditch equipped with fine bubble diffusers and slow speed mixers. *Wat. Res.* (in press).

Hébrard, G. (1995). *Etude de l'influence du distributeur de gaz sur l'hydrodynamique et le transfert de matière gaz-liquide des colonnes à bulles*. Thèse de doctorat, INSA Toulouse no. 363, 174 p.

Héduit, A. and Racault, Y. (1983a). Essais d'aérateurs. Enseignements tirés de 500 essais en eau claire effectués dans 200 stations d'épuration différentes - I) Méthodologie. *Wat. Res.*, **17**(1), 97–103.

Higbie, R. (1935). The rate of absorption of a pure gas into a still liquid during a short time of exposure. *Trans. Am. Inst. Chem. Eng.*, **31**, 365–389.

Jackson, M.L. and Shen, C. (1978). Aeration and mixing in deep tank fermentation systems. *AIChE Journal*, **24**(1), 63–71.

Khudenko, B.M. and Shpirt, E. (1986). Hydrodynamic parameters of diffused air systems. *Wat. Res.*, **20**(7), 905–915.

Pöpel, H.J. and Wagner, M. (1994). Modelling of oxygen transfer in deep diffused-aeration tanks and comparison with full-scale plant data. *Wat. Sci. Tech.*, **30**(4), 71–80.

Roustan, M. (1996). Quels sont les critères d'extrapolation pour les systèmes d'aération? *Tribune de l'Eau*, No. 5–6, 53–58.

Shah, Y.T., Kelkar, B.G., Godbole, S.P. and Deckwer, W.D. (1982). Design Parameters Estimations for Bubble Column Reactors. *AIChE Journal*, **28**(3), 353–379.

Stenstrom, M.K. and Gilbert, R.G. (1981). Effects of alpha, beta, and theta factor upon the design, specification and operation of aeration systems. *Wat. Res.*, **15**, 643–654.

Wagner, M.R. and Pöpel, H.J. (1998). Oxygen transfer and aeration efficiency – Influence of diffuser submergence, diffuser density, and blower type. *Wat. Sci. Tech.*, **38**(3), 1–6.

Wallis, G.B. (1969). *One-dimensional two phase flow*. McGraw-Hill, New York.

Zlokarnik, M. (1978). Sorption characteristics for gas-liquid contacting in mixing vessels. *Adv. Biochem. Eng.*, **8**, 133–151.

Zlokarnik, M. (1998). Problems in the application of dimensional analysis and scale-up of mixing operations. *Chem. Eng. Sci.*, **53**(17), 3023–3030.

Appendix I

	Basin geometry			Diffuser				
Site	Geometry	Submergence (m)	Volume (m^3)	Arrangement	Type	Density (%)	U_G ($m.h^{-1}$)	$IO^5.N_T$ (–)
1	Cylinder	5.2	240	total floor coverage	Disc	8.9	3.5	6.5
		2.2	108			8.9	4.0	7.0
		5.3	243			8.9	5.5	7.0
2	Cylinder	5.5	638	total floor coverage	Disc	4.9	2.0	7.4
		2.3	282			4.9	2.0	7.1
		5.2	597			4.9	3.8	6.7
3	Cylinder	5.9	475	total floor coverage	Disc	7.5	4.5	7.8
		5.9	475			7.5	5.8	8.0
		2.9	243			7.5	5.4	7.7
		2.9	243			7.5	7.4	7.7
4	Cylinder	3.5	347	total floor coverage	Disc	5.3	3.7	7.4
5	Cylinder	3.5	346	1 grid	Disc	6.5	5.9	5.7
6	Cylinder	4.0	397	3 grids	Disc	14.3	7.6	7.0
		4.0	396	2 grids		10.6	8.9	6.6
		4.0	396	I grid		3.7	3.6	5.3
7	Cylinder	3.8	318	1 grid	Disc	8.4	4.9	6.8
8	Cylinder	4.2	757	2 grids	Disc	7.0	4.9	6.4
		4.2	757			7.0	4.8	6.5
9	Cylinder	5.1	757	total floor coverage	Disc	6.8	5.2	7.6
10	Cylinder	5.0	1327	8 grids	Disc	4.5	4.9	5.9
		5.0	1318			4.5	3.3	6.5
		5.0	1318			4.5	1.7	7.5
11	Cylinder	4.6	751	total floor coverage	Tube	12.7	8.4	7.7
		4.6	751			12.7	7.2	8.6
		4.6	750			12.7	5.4	7.4
		4.9	795		Tube	6.1	4.9	7.3
		4.9	795			6.1	4.0	7.1
		4.9	795			6.1	2.9	7.8
12	Cylinder	1.3	0.2	pilot	Disc	34.4	11.0	11.1
		2.7	0.4			34.4	10.9	11.1
13	Cylinder	4.8	850	3 grids	Disc	9.6	5.0	6.2
14	Cylinder	4.6	1451	5 grids	Disc	9.0	4.6	6.6
15	Channel	2.5	1364	10 grids	Disc	5.9	1.6	8.8
		2.5	1364	5 grids		3.0	1.4	6.5
16	Channel	4.1	1572	4grids	Plate	4.5	1.2	6.3
17	Channel	4.2	2070	12 grids	Disc	4.0	3.0	6.4
		4.2	2070	12 grids		4.0	5.9	5.7
18	Channel	2.3	117	2 grids	Tube	5.5	4.4	6.9
19	Channel	4.7	1364	8 grids	Disc	6.5	4.3	5.6
		4.7	1348	8 grids		6.5	2.5	6.0
20	Channel	4.7	1034	4 grids	Disc	4.8	1.9	7.3
21	Channel	3.3	579		Tube	4.9	2.8	6.0
		3.3	579			4.9	5.7	5.3
22	Channel	3.1	216	2 grids	Tube	6.7	3.5	6.5
23	Parallelpiped	7.0	5102	11 grids	Tube	11.4	4.7	6.6
		7.0	2913	4 grids		1.9	1.0	6.0
24	Parallelpiped	3.5	18		Tube	6.9	5.6	8.0
		3.5	18			6.9	5.6	8.2
		3.5	18			6.9	11.2	7.6
		3.5	18			3.5	5.6	6.7
		3.5	18			3.5	8.3	6.1
		3.5	18			3.5	8.3	6.1
25	3/4 cylindric	4.6	1428	total floor coverage	Disc	9.0	2.0	9.1
		3.2	1012			9.0	2.3	8.3
		4.6	1434			9.0	4.9	8.4
		4.0	1250			9.0	5.1	8.4
		4.6	1443			8.9	9.8	7.9
26	Truncated cylinder	4.8	167	1 grid along the wall	Disc	9.9	5.1	6.4