Chapter 9. Agitation and Mixing of Liquids

Agitation (교반): the induced motion of a material in a circulatory pattern

Mixing (혼합): the random distribution of two or more separate phases

→ 원래 정의는 다르지만 많은 경우 혼용해서 사용

Purposes of agitation:

Suspending solid particles (suspension)

Blending miscible liquids (alcohol & water)

Dispersing a gas through the liquid (bubble)

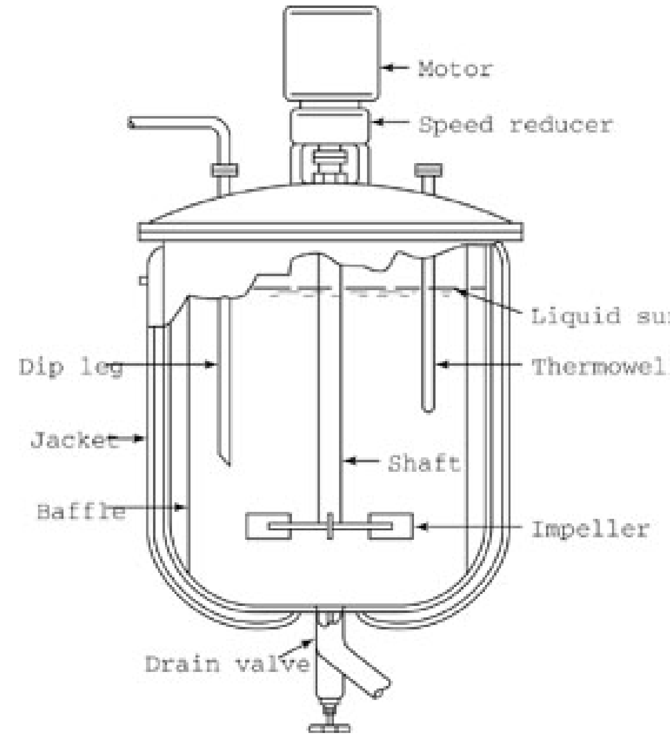
Dispersing immiscible liquids (emulsion)

Promoting heat transfer

Agitated Vessels

: cylindrical form, vertical axis, closed or open top

round bottom, equal liquid depth & tank diameter

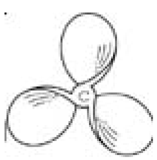


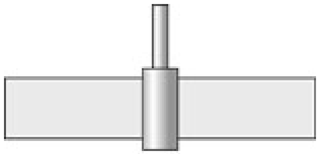
Typical agitation process vessel

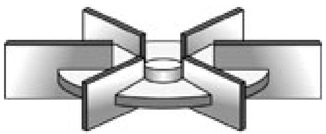
* Impellers

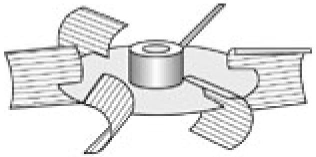
- Axial-flow impellers (축류 임펠러)
- Radial-flow impellers (방사류 임펠러)

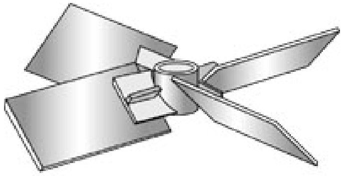
- Impellers for low- to moderate- viscosity liquids:
  - propellers, turbines & high efficiency impellers
- Impellers for very viscous liquids:
  - helical impellers & anchor agitators

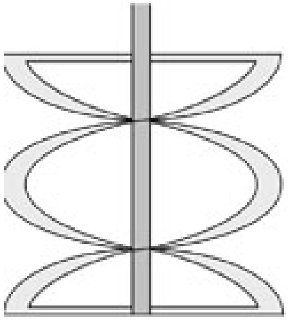

three-blade propeller

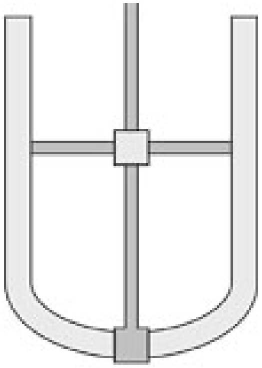

straight-blade turbine


disk turbine

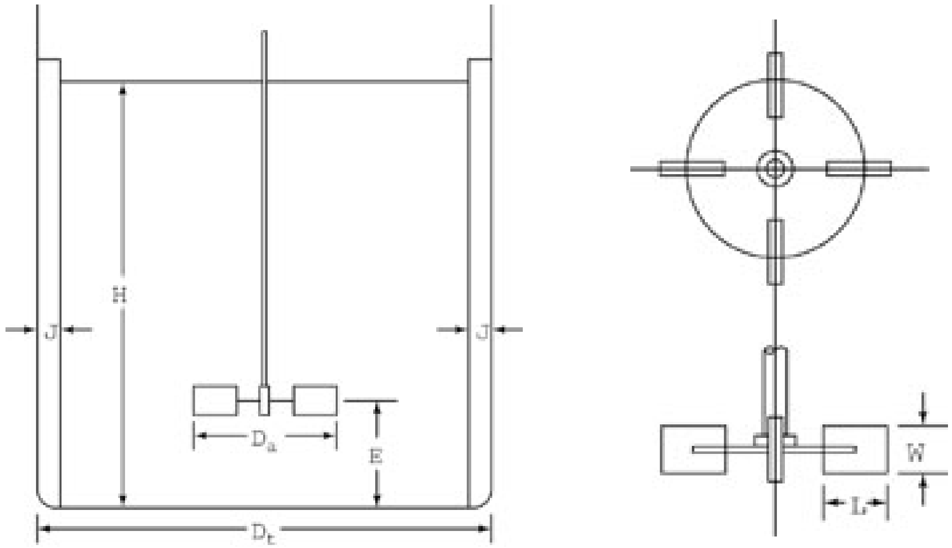

concave-blade disk turbine


pitched-blade turbine


double-flight helical-ribbon impeller


anchor impeller

Standard turbine design



H : depth of liquid

D_t : tank diameter

D_a : impeller diameter

L : blade length

W : impeller width

J : width of baffle

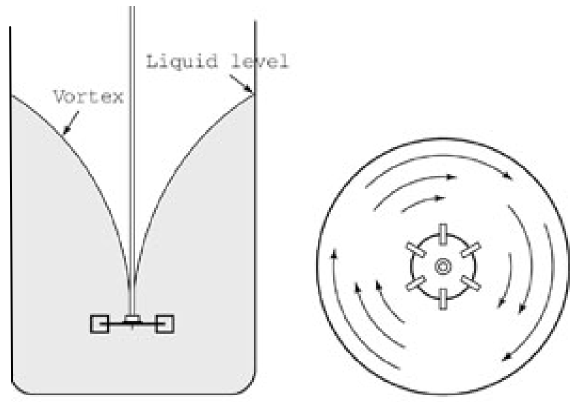
E : clearance

Typical proportions:

$$\frac{D_a}{D_t} = \frac{1}{3} \quad \frac{H}{D_t} = 1 \quad \frac{J}{D_t} = \frac{1}{12} \quad \frac{E}{D_t} = \frac{1}{3} \quad \frac{W}{D_a} = \frac{1}{5} \quad \frac{L}{D_a} = \frac{1}{4}$$

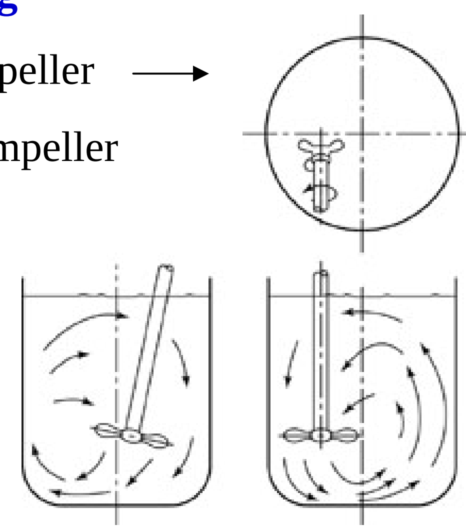
& No. of baffles: 4, No. of impeller blades: 6 or 8

Swirling flow pattern



Prevention of swirling

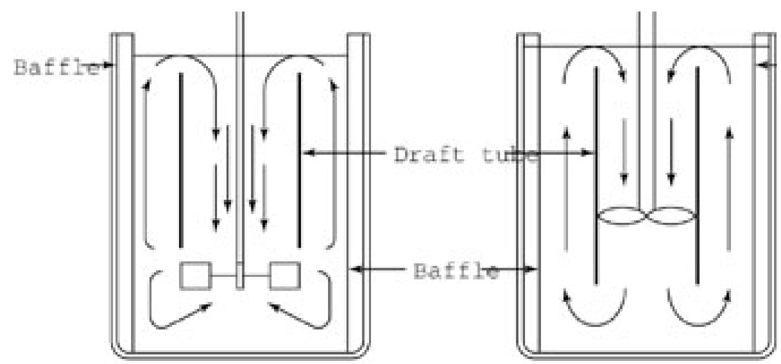
- off-centered impeller →
- side-mounted impeller
- baffles



Draft tubes

Controls direction and velocity of flow

Useful when high shear is desired such as emulsions and suspensions



turbine propeller

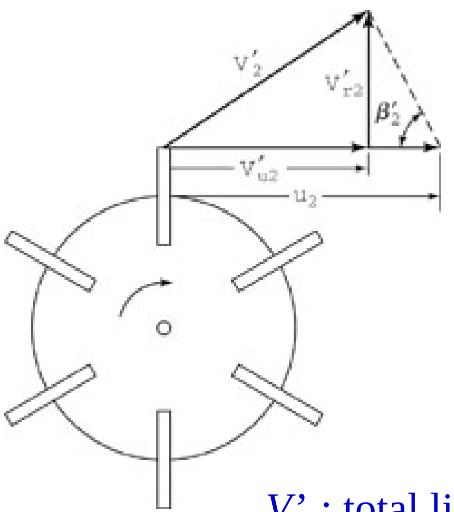
Draft tubes, baffled tank

* Circulation rates

Large impellers at medium speed → promotes flow

Smaller impellers at high speed → generates intense turbulence

Flow number, N_Q



V'_2: total liquid velocity

V'_{u2}: tangential velocity

V'_{r2}: radial velocity

u_2: blade tip velocity

Volumetric flow rate through the impeller

$$q = V'_{r2} A_p$$

V'_{r2} → Eq. (9.5) $\propto \pi D_a n$

A_p → area of the cylinder swept by impeller tip $= \pi D_a W$ → $\propto D_a$

$$\Rightarrow \boxed{q \propto n D_a^3} \quad \text{--- Eq. (9.7)}$$

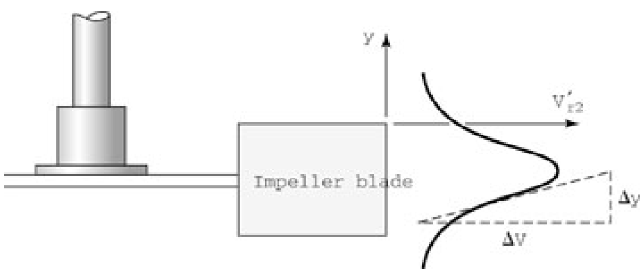
n → rotational speed

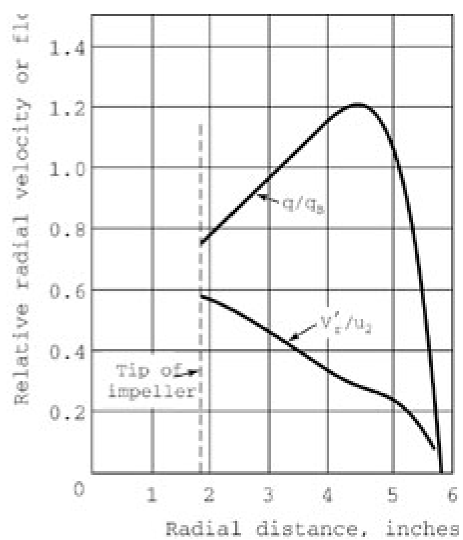
The rate of these two quantities → Flow number, N_Q

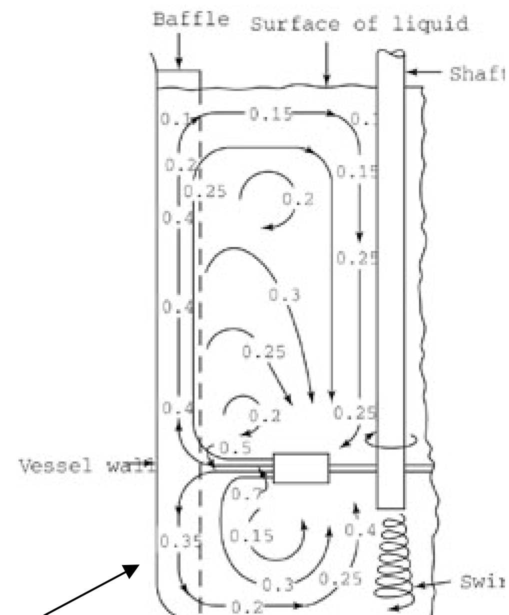
$$N_Q \equiv \frac{q}{n D_a^3} \qquad \text{--- Eq. (9.8)}$$

For a disk turbine:	N_Q=1.3
For marine propellers:	N_Q=0.5
For a four-blade 45° turbine:	N_Q=0.87

* Velocity patterns







Velocity profile and patterns in turbine agitator

Numbers indicate fractions of the velocity of the blade tip.

Tank Reynolds number, Re:

$$\boxed{\mathrm{Re} = \frac{n D_a^{\,2} \rho}{\mu}} \longleftarrow \mathrm{Re} = \frac{D_a u_2 \rho}{\mu} = \frac{D_a (n D_a) \rho}{\mu}$$

$$u_2 \propto \pi D_a n$$

u_2: blade tip velocity

At Re < 10, laminar flow

At Re > 10^4, turbulent flow

*** Power consumption**

Power P: product of the flow rate q and the kinetic energy per unit volume E_k

$$q = n D_a^{\,3} N_Q \qquad E_k = \frac{\rho (V'_2)^2}{2}$$

$$\longleftarrow V'_2 = \alpha u_2 = \alpha \pi n D_a$$

$$P = n D_a^{\,3} N_Q \frac{\rho(\alpha \pi n D_a)^2}{2}$$

$$= \rho n^3 D_a^{\,5} \left(\frac{\alpha^2 \pi^2}{2} N_Q \right)$$

이를 무차원 형태(dimensionless form)로 고쳐 표현하면,

$$\frac{P}{n^3 D_a{}^5 \rho} = \frac{\alpha^2 \pi^2}{2} N_Q \qquad \text{--- Eq. (9.11)}$$

윗 식에서 좌변 항을 Power number (동력수)로 정의함.

Power number, N_P:

$$N_P \equiv \frac{P}{n^3 D_a{}^5 \rho} \qquad \text{--- Eq. (9.12}a\text{)}$$

: ratio of drag force to momentum flow

N_P is analogous to f or C_D

즉, N_P가 크면 동력소비가 큼.

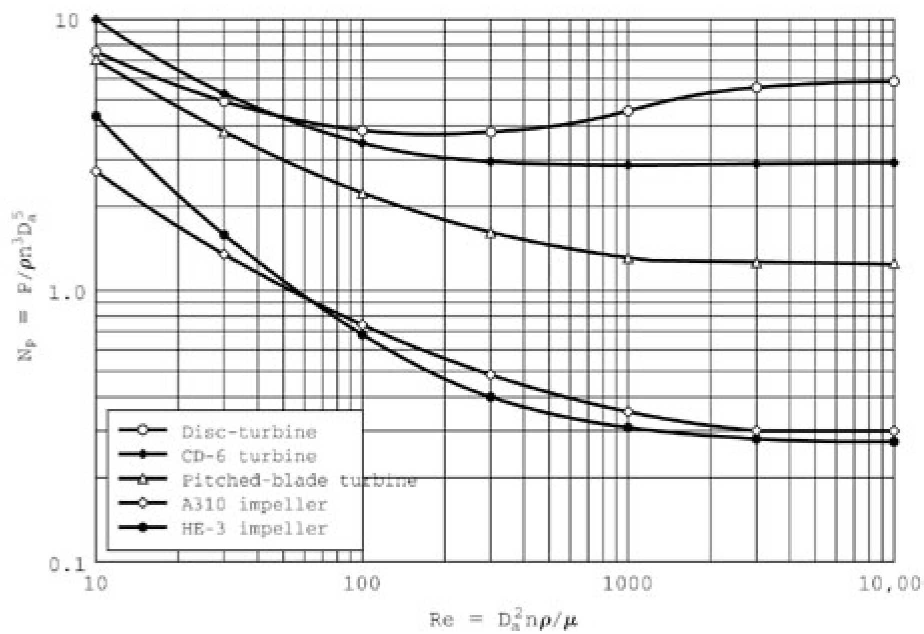


Fig. 9.13 Plots of power number N_P vs. Reynolds number Re for baffled tanks

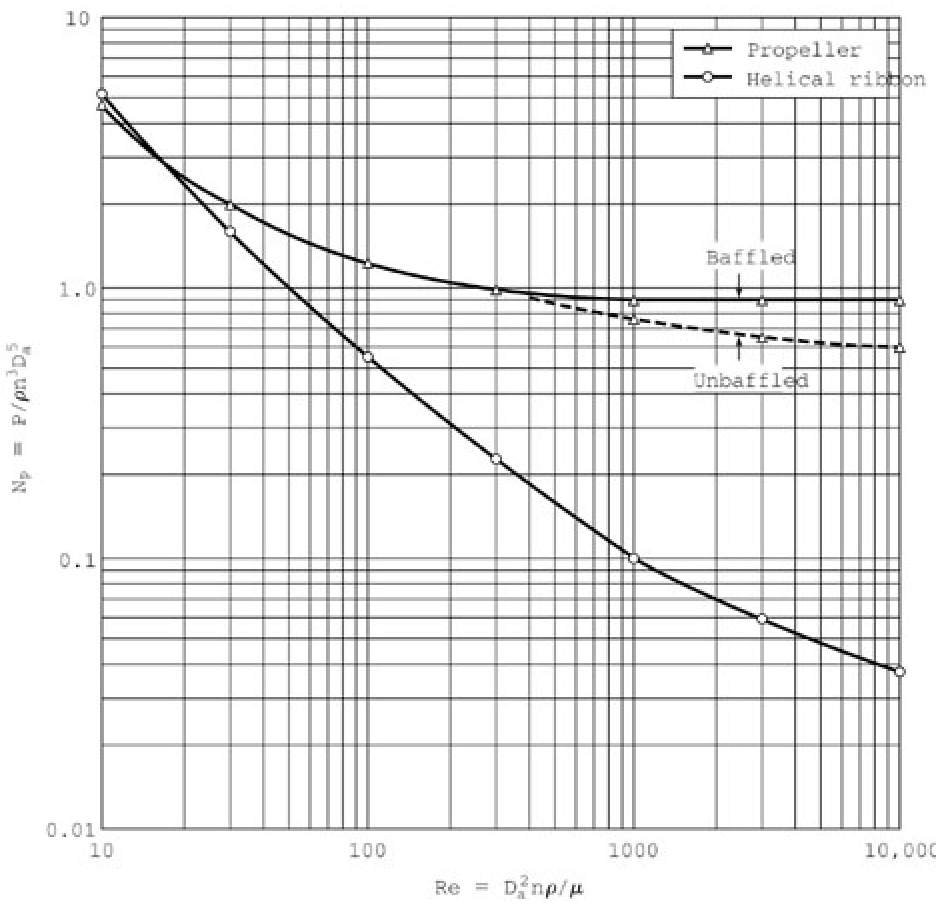


Fig. 9.14 Plots of power number N_P vs. Reynolds number Re for propellers and helical ribbons

Effect of system geometry

- $\frac{D_a}{D_t} \downarrow \longrightarrow \begin{cases} N_P \uparrow & \text{when baffles are few \& narrow} \\ N_P \downarrow & \text{when " many \& wide} \end{cases}$

- $\frac{E}{D_t} \uparrow \longrightarrow \begin{cases} N_P \uparrow & \text{for a disk turbine} \\ N_P \downarrow & \text{for a pitched-blade turbine} \end{cases}$

- Two turbines on the same shaft

  $\longrightarrow$ { 1.9 times power of one turbine when the spacing is longer than D_a
  2.4 times " " for closely spaced turbines

- The shape of tank: little effect on N_P

Calculation of power consumption

The power delivered to the liquid,

$$P = N_P n^3 D_a^5 \rho$$ --- Eq. (9.18) ← from Eq. (9.12*a*)

$$N_P \equiv \frac{P}{n^3 D_a^5 \rho}$$

At low Re (Re < 10),

$$N_P = \frac{K_L}{\text{Re}}$$ for both baffled & unbaffled tanks

$$\therefore P = K_L n^2 D_a^3 \mu$$ --- Eq. (9.20)

← ρ is not a factor

. 상수 K_L & K_T: Table 9.2 (또는 Figs. 9.13-14에서 N_P 값으로 제공)

At high Re (Re > 10,000),

$$N_P \neq ftn\,(\text{Re})$$ for baffled tanks

$$= K_T$$

$$\therefore P = K_T n^3 D_a^5 \rho$$ --- Eq. (9.22)

← μ is not a factor

Ex. 9.1) A disk turbine with 6 blades in a baffled tank 2 m in diameter

Turbine diameter of 0.67 m positioned 0.67 m above the tank bottom

Turbine blade width of 134 mm, A depth of 2 m with 50% NaOH solution

Viscosity of 12 cP, Density of 1,500 kg/m^3, Impeller speed of 90 rpm

What power will be required?

Ans.)

$$\mathrm{Re} = \frac{n D_a^{\,2} \rho}{\mu} = \frac{1.5(0.67)^2 1500}{0.012} \approx 84{,}169$$

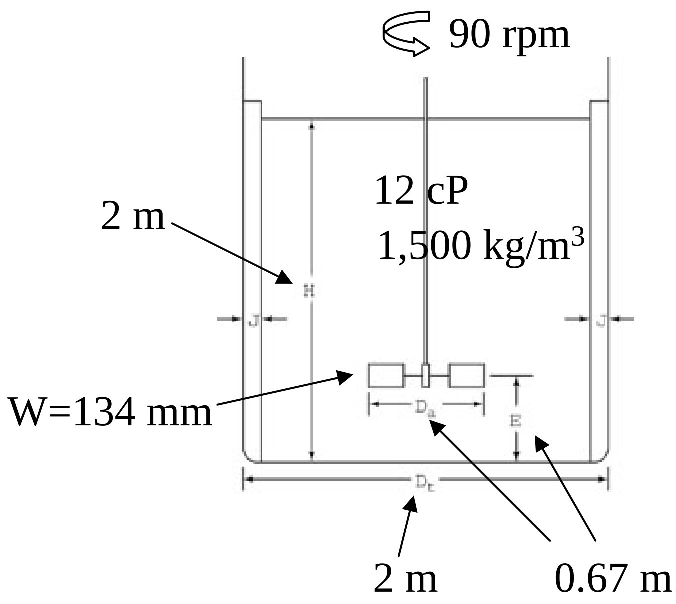
Re >10,000 이므로 $N_P = K_T$ 사용

Table 9.2에서 K_T=5.75

Eq. (9.22)에서 계산하면,

$$P = K_T n^3 D_a^{\,5} \rho = 5.75 \times 1.5^3 \times 0.67^5 \times 1{,}500$$
$$= 3{,}930\ \mathrm{W}$$

μ is not a factor



Ex. 9.2) A disk turbine with 6 blades in a baffled tank 2 m in diameter

Turbine diameter of 0.67 m positioned 0.67 m above the tank bottom

Turbine blade width of 134 mm, A depth of 2 m with a rubber-latex compound

Viscosity of 120 Pa·s, Density of 1,120 kg/m^3, Impeller speed of 90 rpm

What power will be required?

Ans.)

$$Re = \frac{n D_a^2 \rho}{\mu} = \frac{1.5(0.67)^2 1120}{120} \approx 6.3$$

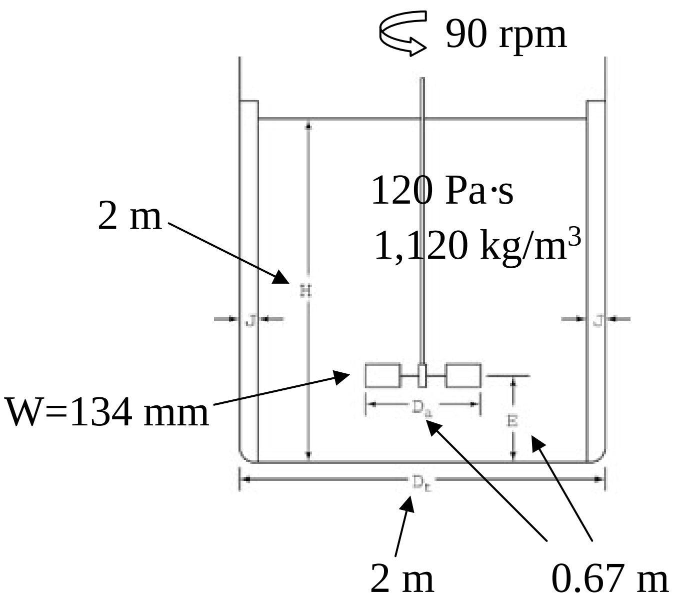
Re <10 이므로 $N_P = K_L/Re$ 사용

Table 9.2에서 K_L=65

Eq. (9.20)에서 계산하면,

$$P = K_L n^2 D_a^3 \mu = 65 \times 1.5^2 \times 0.67^3 \times 120$$
$$= 5{,}278\,\text{W}$$

ρ is not a factor



Blending and Mixing

Mixing time (혼합시간) t_T : the time to reach complete mixing (99% mixing)

← achieved if the contents of the tank are circulated about 5 times

$$t_T \approx \frac{5V}{q_T}$$

↓

nt_T vs. Re

(Reynolds 수에 따른 혼합시간)

V : liquid volume in tank

q_T : total liquid flow rate

n : rotational speed (r/s)

ex) For turbine in a baffled tank

with D_a/D_t=1/3, D_t/D_H=1

→ nt_T=36 for Re > 2,000

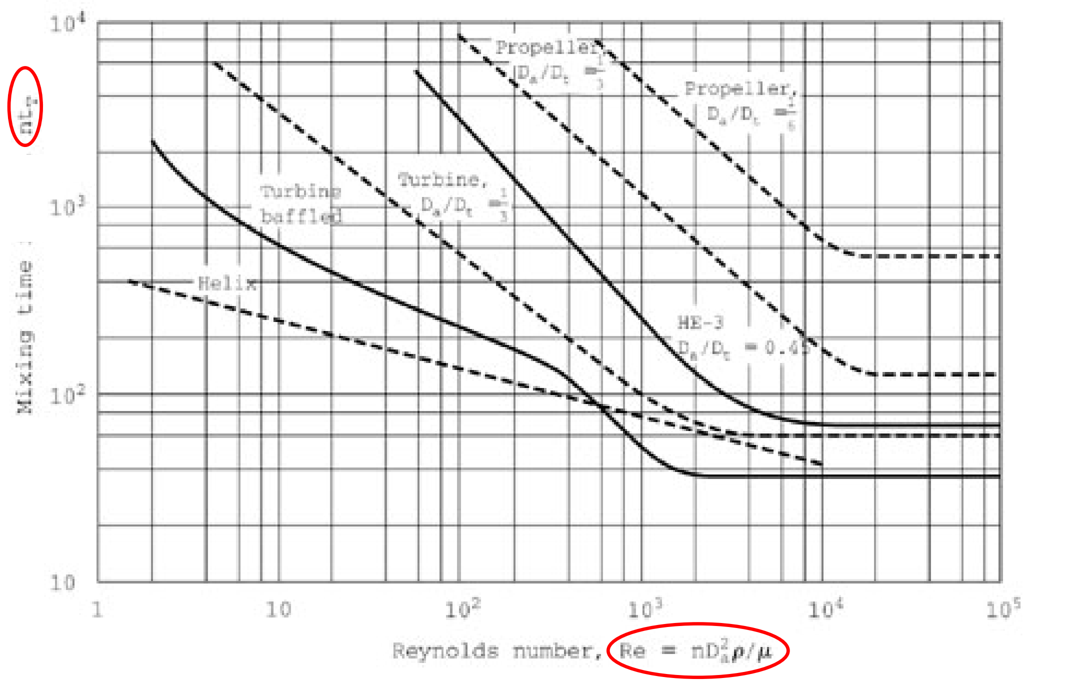
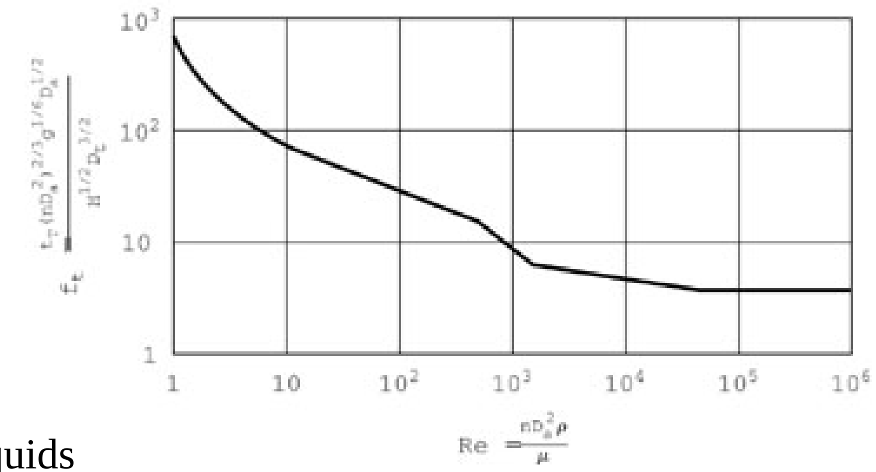


Fig. 9.16. Mixing times in agitated vessels.
Dashed lines for unbaffled tanks; Solid lines for baffled tanks.

Mixing time factor (혼합시간 인자) f_t

A general correlation for turbines:

$$f_t = nt_T \left(\frac{D_a}{D_t}\right)^2 \left(\frac{D_t}{H}\right)^{1/2} \left(\frac{g}{n^2 D_a}\right)^{1/6}$$



A helical ribbon agitator:

shorter mixing times with very viscous liquids

In a pseudoplastic liquid: blending time is much longer than in Newtonian liquids.

Ex. 9.3) D_t = 6 ft (1.83 m), 6-straight blade turbine, D_a = 2 ft (0.61 m), $E = D_a$, n = 80 rpm, $H = D_t$

For neutralizing a NaOH solution with HNO_3 solution at 70 ºF, t_T = ?

Ans.) From Appendix 6 → $\rho = 62.30\,\text{lb/ft}^3 = 62.30(0.453\text{kg/lb})(\text{ft}/0.305\text{m})^3 = 997\text{kg/m}^3$

$$\mu = 0.982\text{cP} = 9.82\times10^{-4}\,\text{Pa}\cdot\text{s}$$

$$\therefore \text{Re} = \frac{nD_a^{\ 2}\rho}{\mu} = 503{,}000$$

From Fig. 9.16 for Re = 503,000, nt_T = 36 → t_T = 36/1.333 = 27s

Dispersion Operations

Volume (or holdup) of dispersed phase Ψ

$$\Psi = \frac{\pi N D_p^3}{6}$$

N : the number of drops or bubbles per total volume

Total surface area of drops per total volume a

$$a = \pi N D_p^2 \longrightarrow D_p = \frac{6\Psi}{a}$$

(실제로는 입자의 크기가 다르므로 평균입자경으로 정의)

Sauter mean diameter $\overline{D}_s$ (or volume-surface mean diameter D_{32})

$$\overline{D}_s \equiv \frac{6\Psi}{a}$$

*** Liquid/liquid dispersion**

Weber number We

$$We = \frac{\rho_c (n D_a)^2}{\sigma / D_a} = \frac{\rho_c n^2 D_a^3}{\sigma}$$

: kinetic energy/surface energy

(ρ_c: density of continuous phase; σ: interfacial tension)

$$\overline{D}_s / D_a \propto We^{-0.6} \longrightarrow We \uparrow \rightarrow \overline{D}_s \downarrow$$

Related problems: (Probs.) 9.1, 9.3, 9.5, 9.11(a) and 9.18