Bakker A., Benz G.T. (1996) Mixing in Industrial Fermenters. 10th International Biotechnology Symposium, August 25-30, 1996, Sydney, Australia.

Mixing in Industrial Fermenters

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Presented at: 10th Int. Biotechnology Symposium
August 25-30, 1996, Sydney, Australia

ABSTRACT

Efficient fermenter operation depends on a variety of mixing related variables. Gas-liquid mass transfer, proper feed distribution, local oxygen concentration, shear rate distribution, and local mixing intensity all affect the productivity of the reactor. The viscous properties of the fermentation medium play an important role, especially for strongly non-Newtonian fluids such as xantham gum. In that case efficient mixing is particularly important, but difficult to achieve. This paper discusses how mixing in industrial fermenters can be optimized using a combination of computer modeling and experimental laboratory testing.

Experimental laboratory testing is an important step in the reactor design, to verify computer simulations, to gather data for systems that have not been previously researched and to develop new impeller systems. Most newly built, large fermenters (> 500 HP) employ combinations of concave blade turbines to disperse the gas and high efficiency impellers to provide efficient overall mixing. The application of such systems will be illustrated with industrial examples.

Computational fluid mixing models for industrial fermenters have only recently become available. The fermenter is divided into a computational grid with between 2000 and 300,000 cells depending on the required accuracy. For each cell, conservation equations for mass, momentum, energy, turbulence, gas fraction and bubble size are solved. The result is a detailed map of both the flow field and local mass transfer rate in the reactor. These results can in principle be coupled with a kinetic growth model to calculate local microorganism growth. Regions of low and high productivity or possible oxygen starvation can then easily be identified. Modifications to the impeller system and reactor design can then be made to improve the fermenter's performance. The proper application of these techniques will allow for more accurate scale-up from pilot reactor to industrial scale.

Fermentation

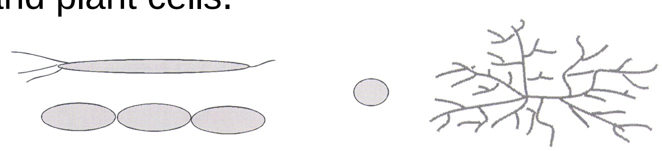
- Fermentations are reactions wherein a raw organic feed is converted into product by the action of microbes or enzymes:

$$(\text{organic feed, A}) \xrightarrow[\text{as catalyst}]{\text{Enzyme E}} (\text{product chemicals, R})$$

$$(\text{organic feed, A}) \xrightarrow[\text{as catalyst}]{\text{Microbe C}} (\text{R}) + (\text{more cells, C})$$

Micro-Organisms

- Various types of micro-organisms exist: bacteria, fungi (yeasts, molds), animal, insect, and plant cells.



- Rheology depends on concentration and morphology of organisms and carriers.
- Newtonian, non-Newtonian, visco-elastic.

Design Issues

- Aerobic vs. Anaerobic
  Aerobic requires gas sparging
  Mass transfer
- Rheological properties
- Batch, Semi-Batch, Fed Batch, Continuous
- Heat removal
- Blend time
- Feed concentration

Possible Mixing Related Problems

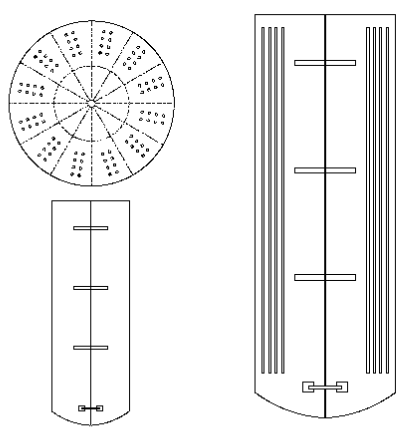
- Oxygen starvation or poisoning (local or global)
- CO_2 or other product poisoning (local or global)
- Heat damage
- Shear damage
- Nutrient starvation
- Selectivity

Mixture Homogeneity

- Mixture homogeneity affects selectivity, which determines product composition.
- High degree of homogeneity required for “single product” processes (e.g most pharmaceuticals, industrial alcohol).
- High degree of homogeneity not necessarily desirable for certain flavor dependent food products (e.g. wine and beer).

Types of Fermenters

- STIRRED TANK
- Airlift
- Bubble columns
- Hollow fiber
- Fluidized bed



Design Example

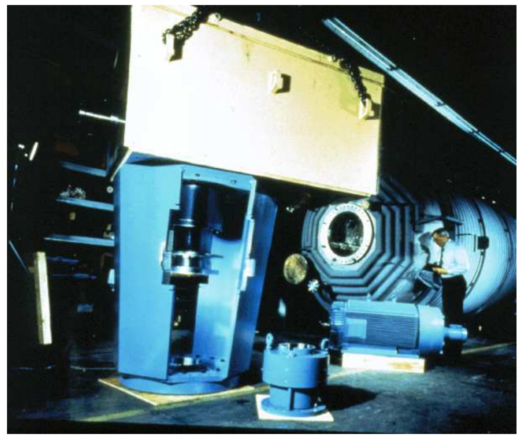
- Aerobic fermenter
- Vessel diameter 5.8 m
- Total height 21 m
- Batch volume up to 450 m^3.
- Fed batch: batch time 5 days.
- Viscosity in 50 - 100 mPa-s range
- Superficial gas velocity 0.1 m/s or 1 vvm

Process Requirements

- $k_l a$ around 0.1 1/s
- O_2 Uniformity: blend time order of $1/k_l a$ combined with good gas dispersion
- No dead zones, rapid mixing of feed
- Sufficient flow around cooling coils

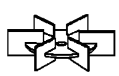
Mixer

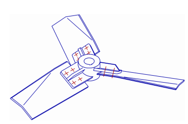
- Impeller system
- Power input
- Impeller speed
- Mechanical feasibility



Impellers

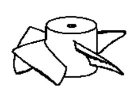
- Radial pumping gas dispersion impellers: D-6 (Rushton), CD-6 (Concave blade)



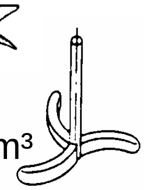


- Axial pumping impellers:
  – HE-3 (narrow blade hydrofoil)
  – Maxflo-T (wide blade hydrofoil)

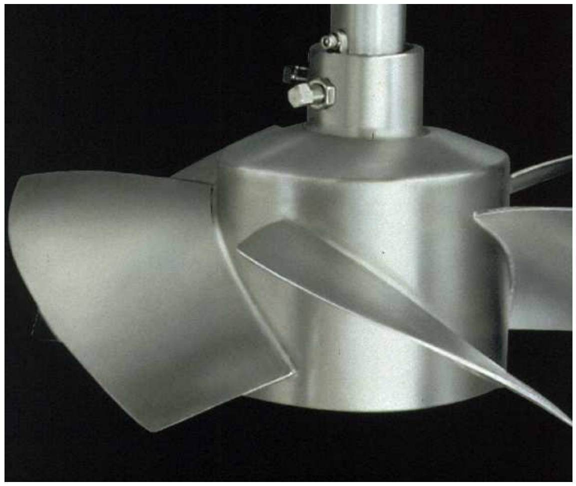
  Low shear, high flow



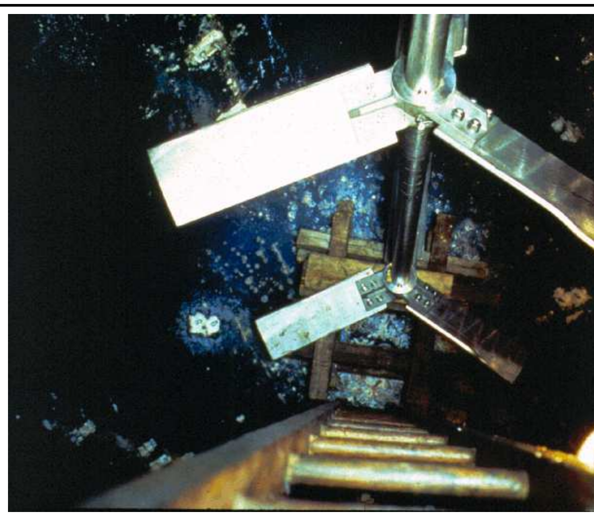
- Pfaudler Retreat Blade: glass lined < 40 m^3



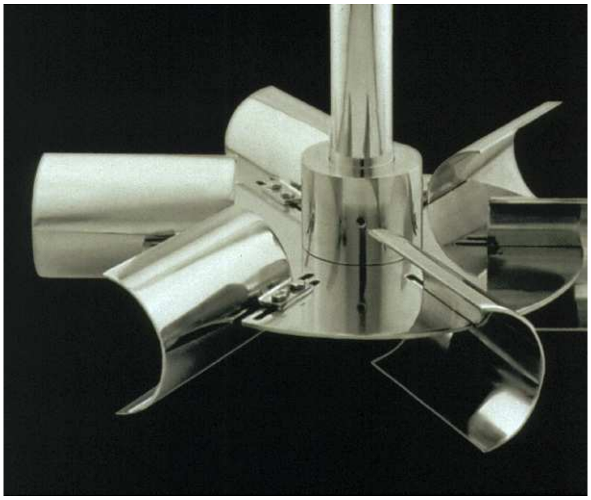
Maxflo-T Impeller



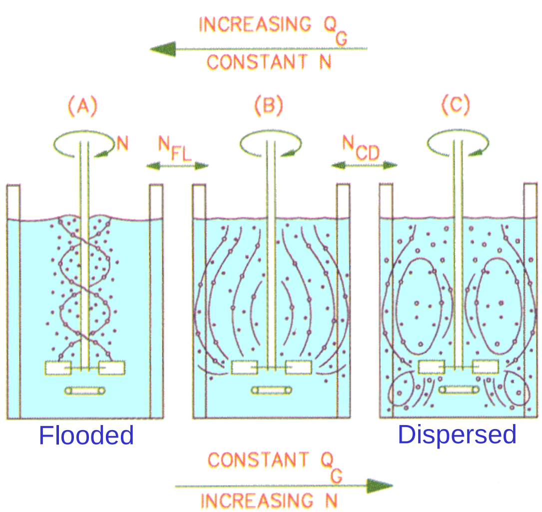
HE-3 Impeller



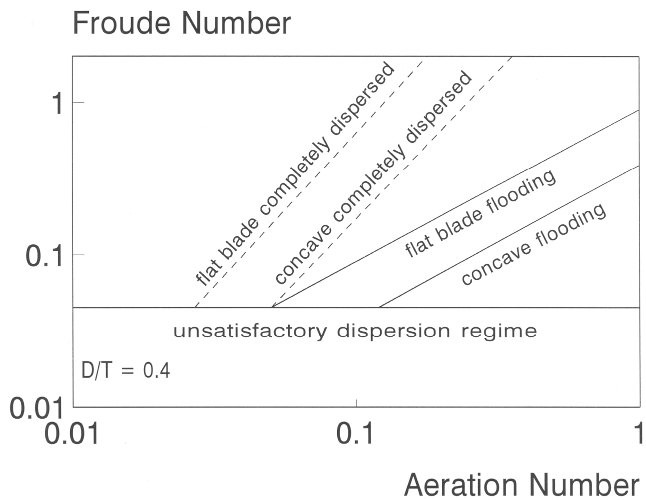
CD-6 Impeller



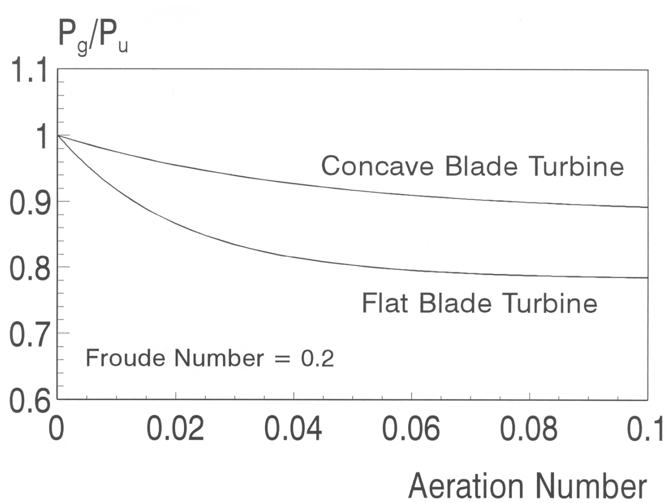
Gas-Liquid Flow Regimes



Flow Regime Comparison D-6 and CD-6



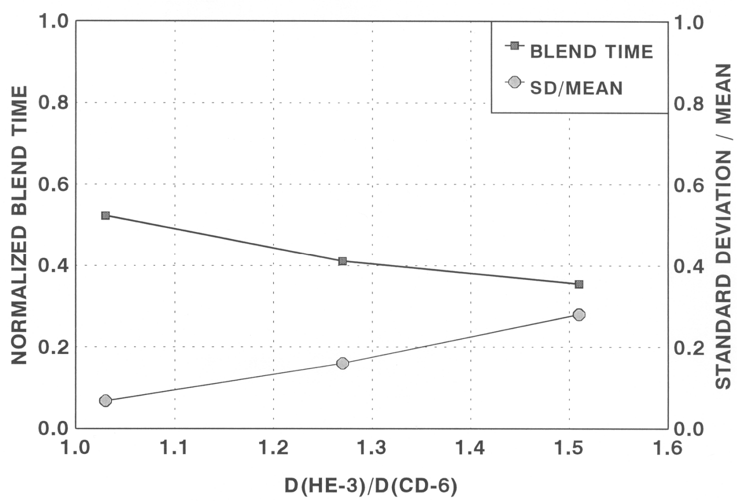
Ratio Gassed to Ungassed Power Draw



Impeller System Options

- Multiple impellers required
- All radial flow
- All axial flow
- Bottom up-pumping, top down pumping
- Bottom radial flow, rest axial flow

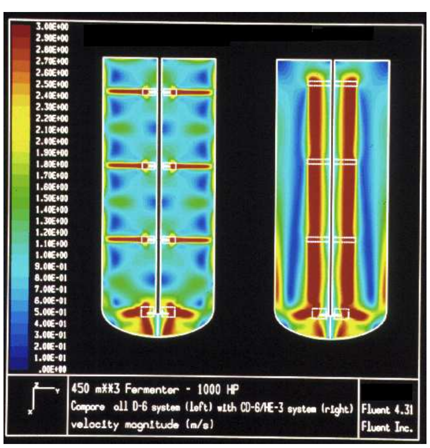
Ratio between CD-6\HE-3 Blend Time and All D-6 Blend Time

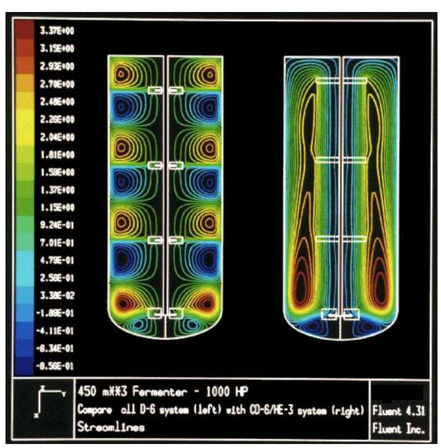


Compare Flow Patterns

- Use computational models to calculate the flow patterns for the various impellers.
- Tank is divided in grid cells (up to 300,000 depending on type of model).
- Solve equations of momentum, continuity, etc. for each cell.
- Impellers are modeled using boundary conditions obtained using laser-Doppler velocimetry.

Flow Pattern Comparison

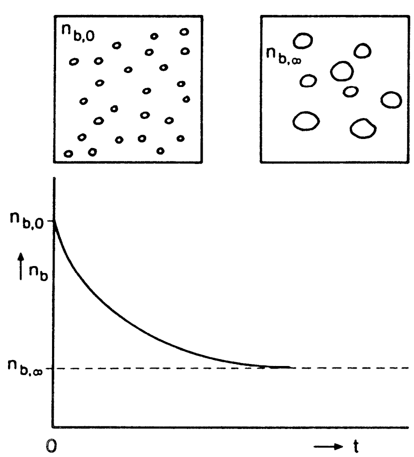




Gas Dispersion Modeling

- Use computational models for full scale predictions.
- Computational model for gas dispersion calculates local gas holdup, local bubble size, and local $k_l a$.
- Bubble size model based on population balance and takes effect of break-up and coalescence into account.
- $k_l a$ follows from local holdup, bubble size, and turbulence intensity.

Bubble Size Modeling



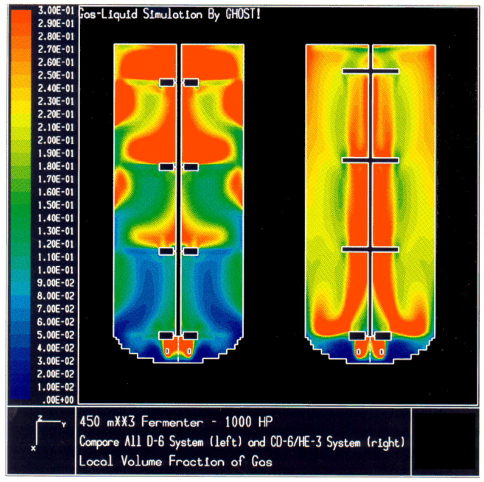
$$\frac{\partial n_b}{\partial t} + \vec{\nabla}.\left(n_b \vec{u}_g\right) = \omega\left(n_{b\infty} - n_b\right) + \frac{S_g}{V_{b,in}}$$

$$n_b = \frac{\alpha}{V_b}$$

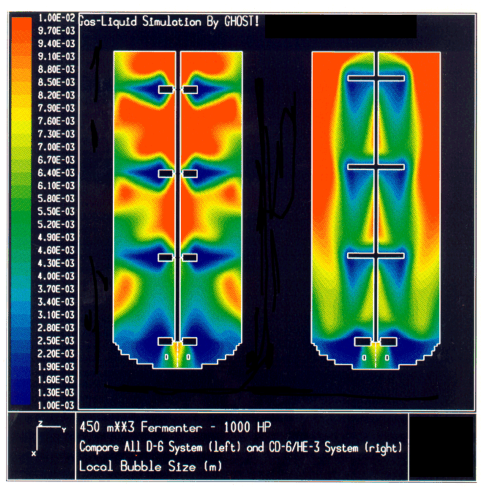
$$\omega = C_\omega \frac{3}{2}\sqrt{2}\,\frac{\alpha}{d_b}\left|\vec{u}_g^{\,\prime}\right|$$

$$d_{b\infty} = C_{b\infty}\left(12\,\frac{\sigma}{\rho_l}\right)^{\frac{3}{5}} \epsilon^{-\frac{2}{5}}$$

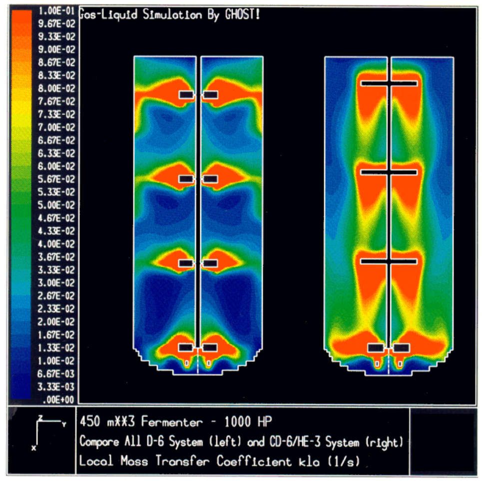
Local Volume Fraction



Local Bubble Size



Local Mass Transfer Coefficient $k_l a$



Heat Transfer Coils

- Twelve sets of eight vertical cooling coils that also act as baffles.
- Water cooled.
- Verify there is sufficient liquid movement around the coils.
- Computer model for 30º section of tank; 250,000 nodes.

Heat Transfer Correlations

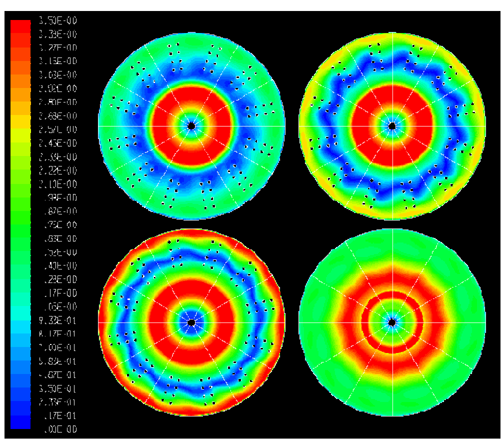
- Total heat transfer resistance includes wall resistance, resistance cooling liquid side, fouling, etc.
- Process side heat transfer coefficient:

$$\mathrm{Nu} = k_{imp} \; f_{geo,visc} \; \mathrm{Re}^{2/3} \, \mathrm{Pr}^{1/3}$$

- Process side heat transfer coeff. ~ $P^{0.29}$
- Cooling capacity approx. 8000 kW from correlations.

Flow Field Around Coils

- This image shows the velocity magnitude in four cross sections. From top left to bottom right, at 0.8, 0.6, 0.4, and 0.2 fraction of the liquid level off the bottom.
- The simulations show that there is sufficient liquid movement around the cooling coils.



Final Design

- 1000 HP motor at 105 RPM loaded 80% under gassed conditions

  (second speed 52.5 RPM)

  (hollow shaft 0.42 m diameter)
- One CD-6 and three HE-3 impellers
- Estimated gas hold-up 23%; P_g/P_u = 0.65
- $k_l a$ = 0.10 1/s; blend time = 40 s

Experience with Final Design

- Performed as designed and operates as hoped.
- More than sixty of these 1,000 HP units have been built for various fermentations.
- Total installed CD-6\HE-3 systems approximately 94,000 HP.

Conclusions

- Gas dispersions can never be homogenous.
- Most mass transfer will occur in impeller regions.
- Good top to bottom blending performance is essential.
- Systems with a lower gas dispersing impeller and upper axial flow impellers are ideally suited for large scale fermentations