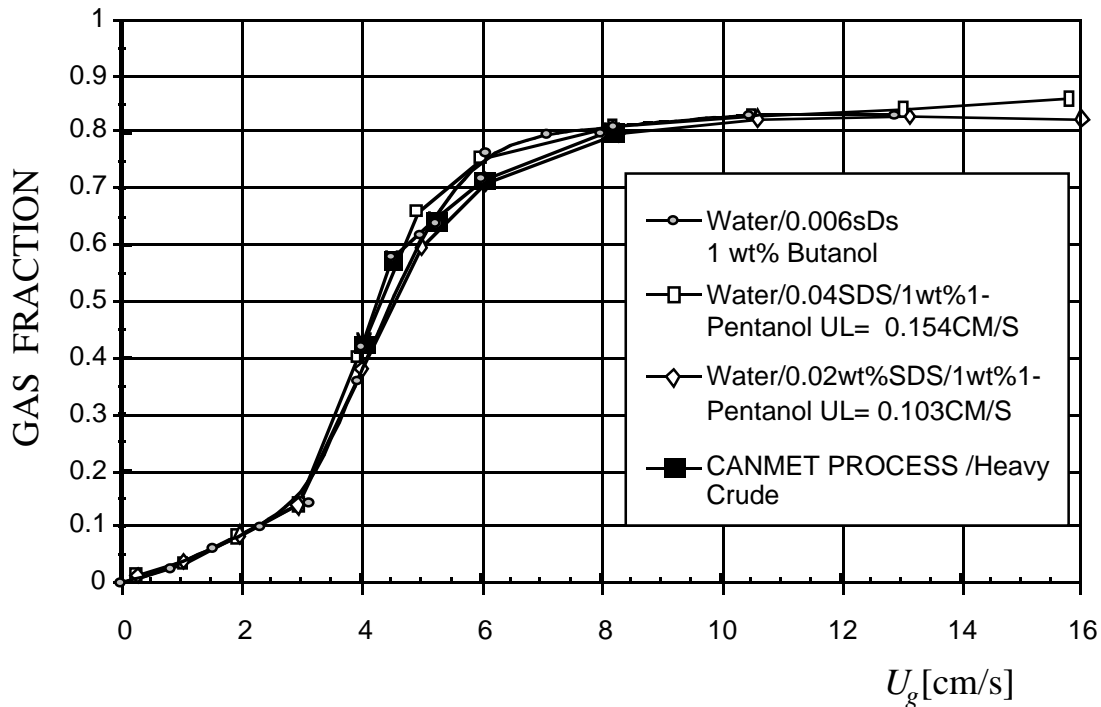


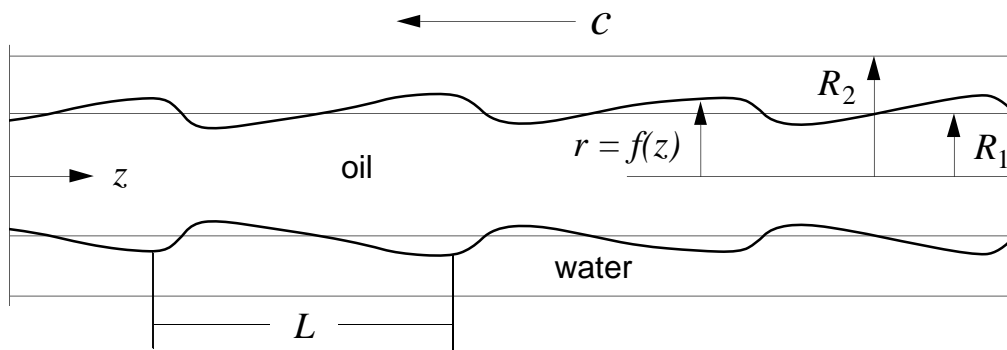
THE CANMET PILOT CAN BE SIMULATED BY AQUEOUS SYSTEMS USING MANY DIFFERENT SURFACTANTS



Gas holdup as a function of gas velocity

CANMET hydrocracker. 2 meters diameter with capacity of 800 tons/day, operates at 400°C at liquid velocities of 0.1 - 0.2 cm. You can match the response of this foaming, commercial hydrocarbon reactor by bubbling gas through water plus surfactants. You can have success with many different surfactants.

Theory and direct simulation



Axisymmetric and L-periodic

Oil and Water have the same density

The holdup ratio h is prescribed where

$h = c / c_w =$ average oil velocity / average water velocity.

$h = 1$ oil and water are well mixed; emulsions

$h = 2$ Perfect CAF (no wave), Rigid core

$h^a \approx 1.4$ wavy core flow, experiments

$e = \eta_w / \eta_o$ viscosity ratio

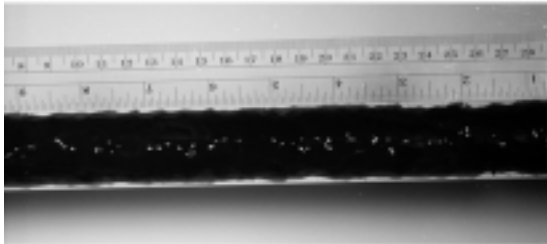
R_1 mean core radius

$Re = c(R_2 - R_1) / \eta_w$

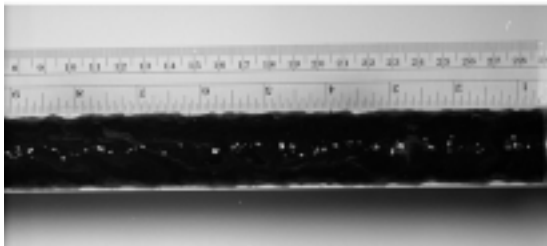
Horizontal Flow of Oil and Water with Fixed Water Velocity and Varying Oil Velocities

Water flow fixed at 1.0 gallons per minute

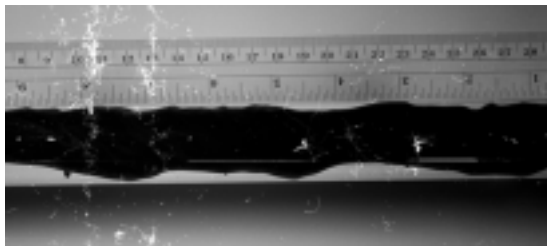
Oil Flow rates:



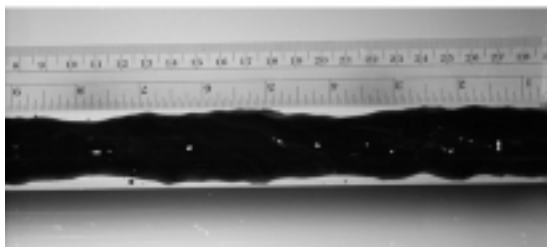
6.075 gallons per minute



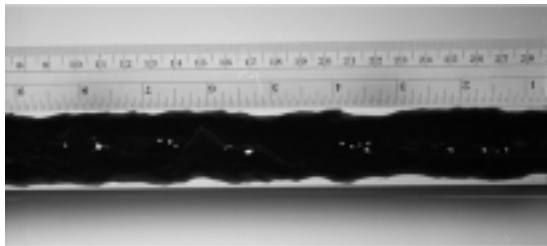
8.2 gallons per minute



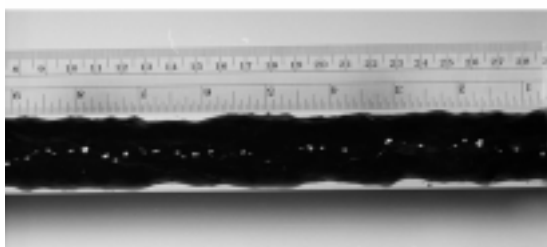
10.125 gallons per minute



12.15 gallons per minute

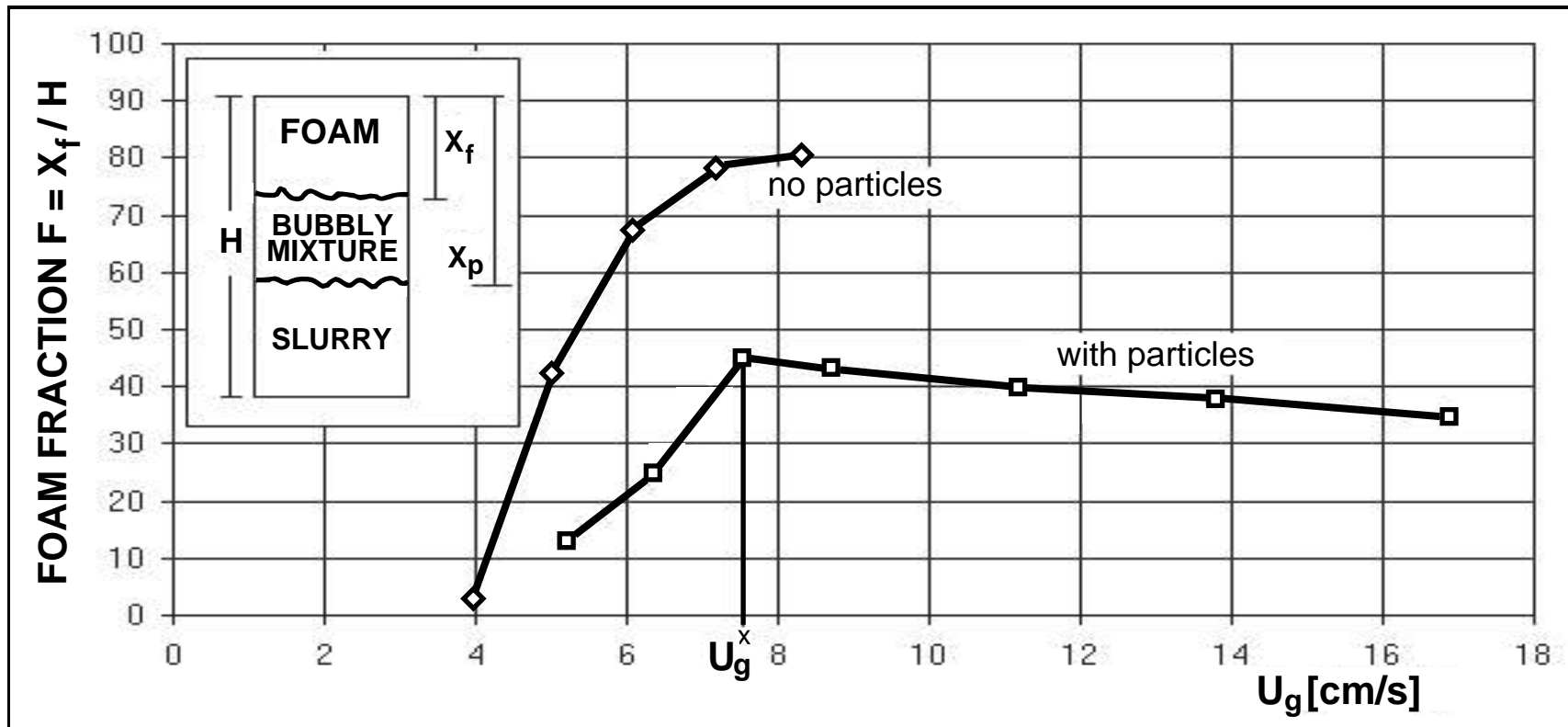


14.175 gallons per minute



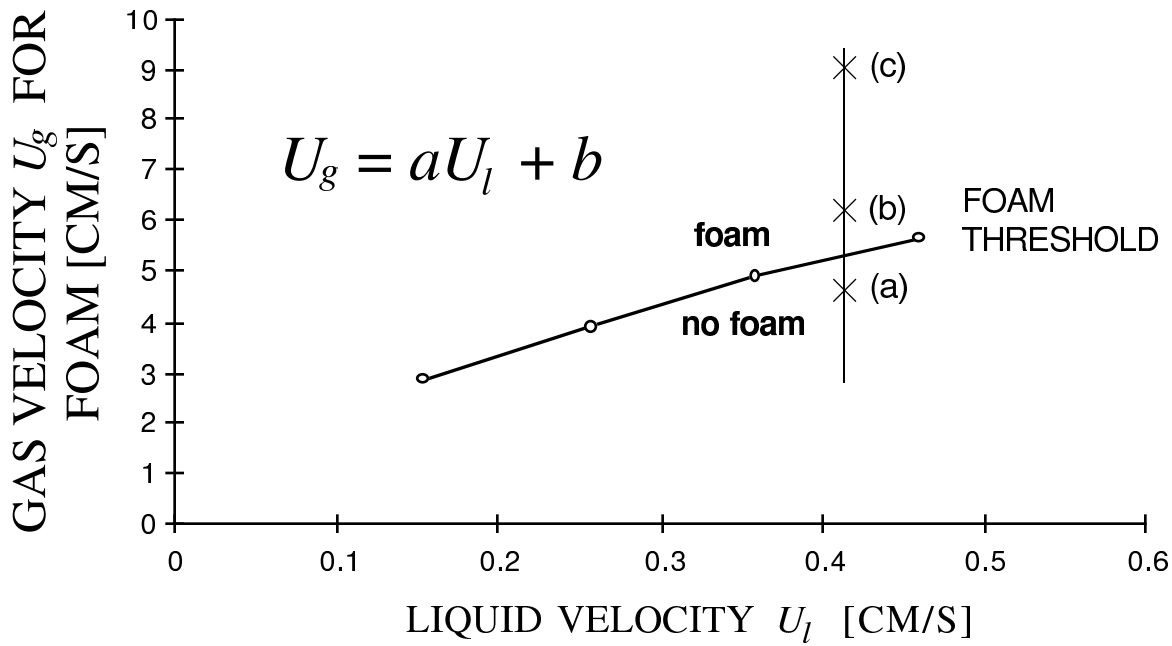
16.2 gallons per minute

FOAM CONTROL USING A FLUIDIZED BED

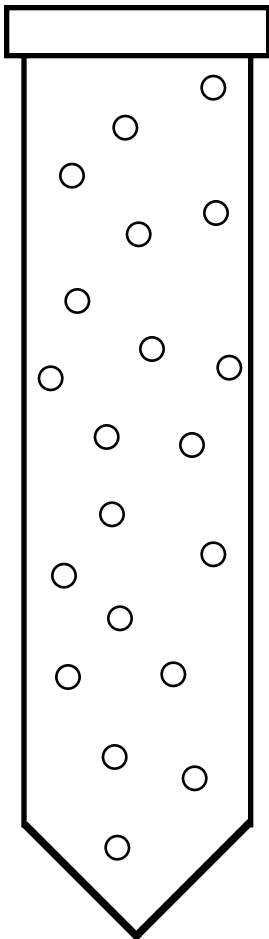


Suppression of foam due to fluidization of 532 nm glass particles, 10% by volume, at a liquid velocity of $U_l = 0.257$ cm/s.

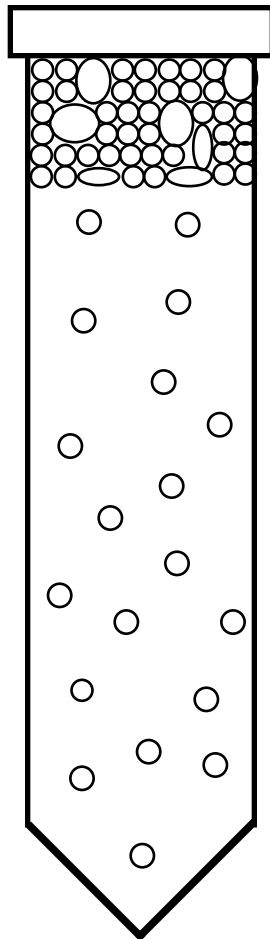
**FOAM PRODUCTION AND BED EXPANSION
COMPETE**



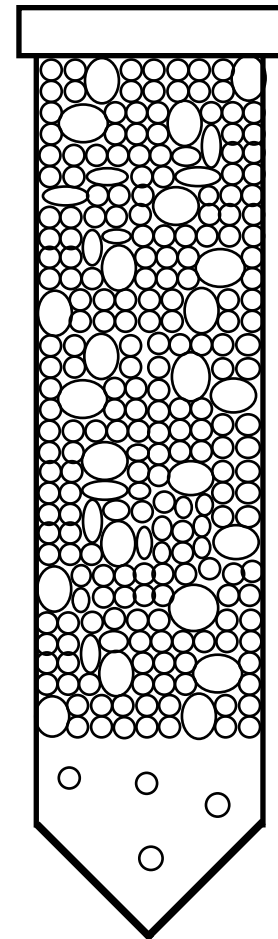
FOAM THRESHOLD FOR INCEPTION OF FOAMING SDS (0.04%) and pentanol (1%) in water



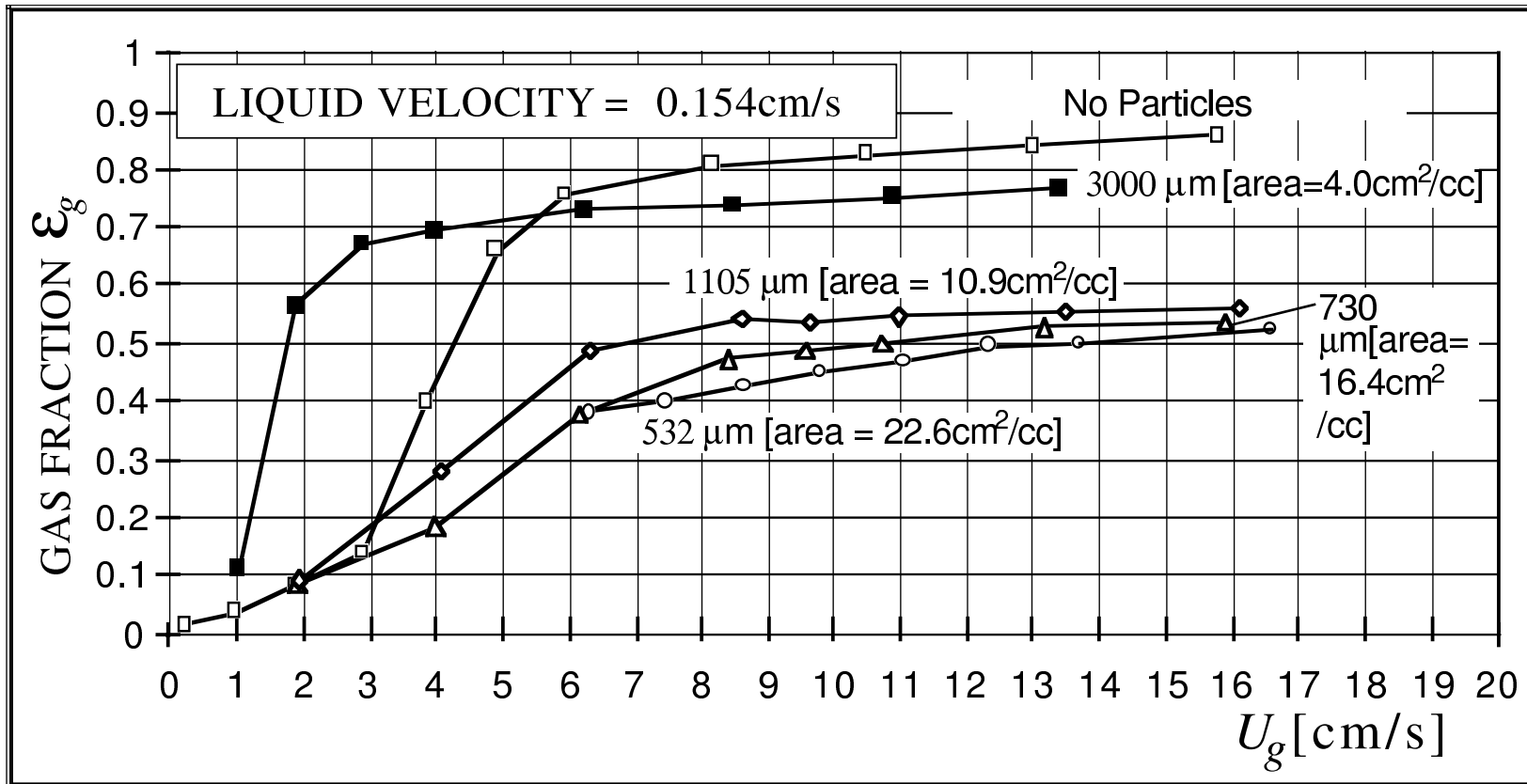
(a) no foam



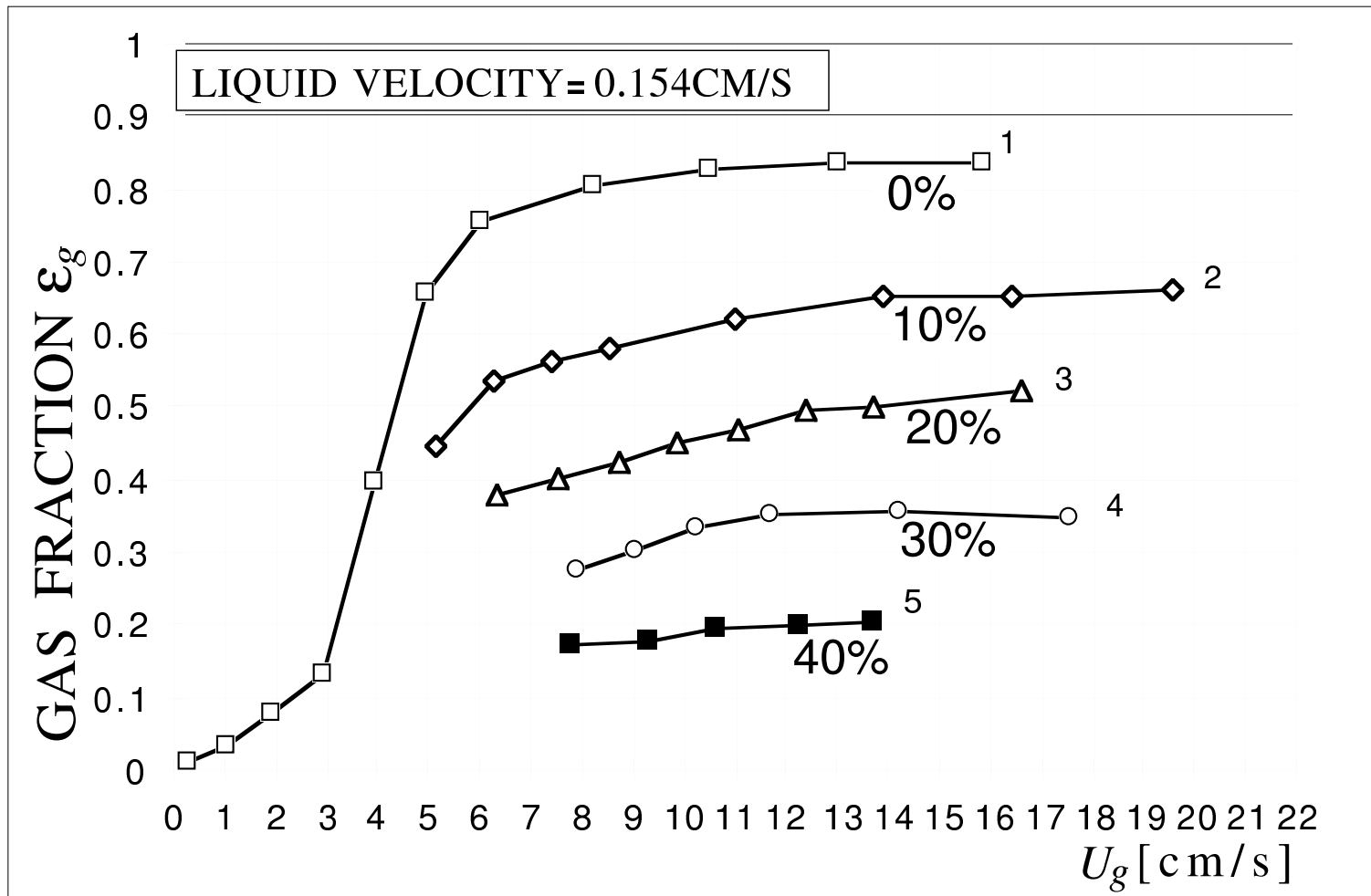
(b) little foam



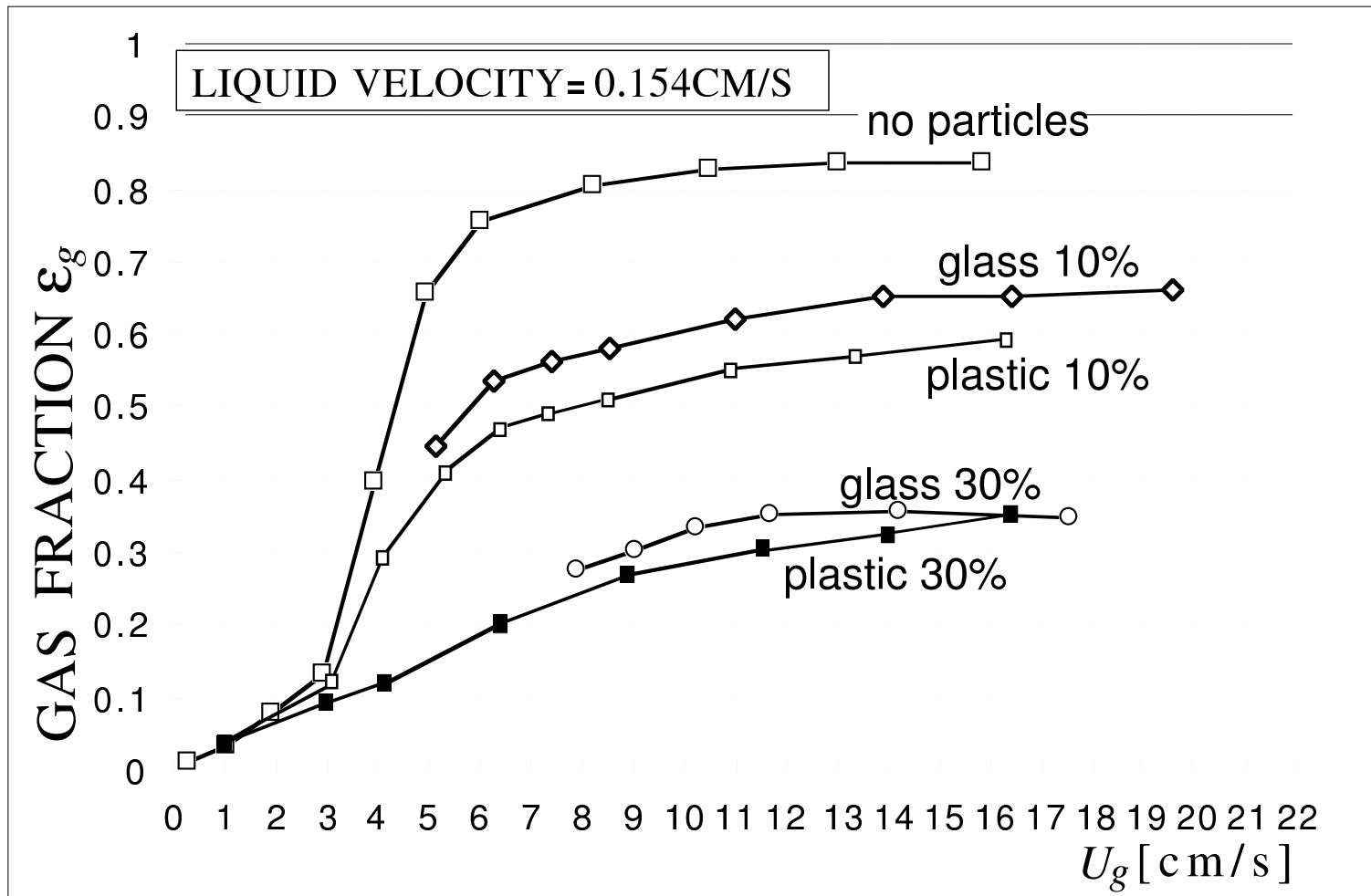
(c) more foam



Effect of particle size and wetted area of solids on the gas fraction for glass particles of batch fraction 10%. The gas fraction increases with the diameter and decreases with the area of particles.



Gas fraction as a function of gas velocity for batch solids fractions of ϵ_p of 532 μm glass spheres. The gas fraction decreases with ϵ_p ; the liquid fraction increases.



Gas fraction as a function of gas velocity for batch solids fractions of ϵ_p of 532 μm glass spheres. The gas fraction decreases with ϵ_p ; the liquid fraction increases.

Equations: Eliminate $\mu_0 = \mu_w/\varepsilon$

$$\rho \mathbf{v} \cdot \nabla \mathbf{v} = -\beta \mathbf{e}_z - \nabla \phi + \mu_w \nabla^2 \mathbf{v} \quad \text{water}$$

$$\rho \mathbf{u} \cdot \nabla \mathbf{u} = -\beta \mathbf{e}_z - \nabla \Psi + \frac{\mu_w}{\varepsilon} \nabla^2 \mathbf{u} \quad \text{oil}$$

Interface conditions on $r = f(z)$

$$\mathbf{u} = \mathbf{v} \quad \text{velocity is continuous}$$

$$\mathbf{v} \cdot \mathbf{n} = \mathbf{u} \cdot \mathbf{n} = 0 \quad \text{normal component vanishes}$$

$$\boldsymbol{\tau} \cdot \mathbf{D}[\mathbf{u} - \varepsilon \mathbf{v}] \cdot \mathbf{n} = 0 \quad \text{The shear stress is continuous}$$

$$-\phi + \Psi + \mu_w \mathbf{D}[\mathbf{v} - \mathbf{u}/\varepsilon] = \frac{\sigma}{f(1-f'^2)^{\frac{1}{2}}} - \frac{\sigma f''}{(1+f'^2)^{\frac{3}{2}}}$$

Additional conditions

$$\mathbf{v} = -c \mathbf{e}_z \text{ on } r = R_2, L - \text{periodic,} \\ \text{div} \mathbf{u} = \text{div} \mathbf{v} = 0$$

Perturbation solution

$$\mathbf{v} = \mathbf{v}_0 + \varepsilon \mathbf{v}_1 + \varepsilon^2 \mathbf{v}_2 + \dots \quad \text{water}$$

$$\mathbf{u} = \varepsilon \mathbf{v}_1 + \varepsilon^2 \mathbf{u}_2 + \dots \quad \text{oil}$$

The core is rigid at zeroth order $\mathbf{u}_0 \equiv 0$

$$\phi = \phi_0 + \varepsilon \phi_1 + \varepsilon^2 \phi_2 + \dots \quad \text{water}$$

$$\Psi = \Psi_0 + \varepsilon \Psi_1 + \varepsilon^2 \Psi_2 + \dots \quad \text{oil}$$

The pressure at zeroth order is not uniform. The domain f and L must be perturbed

$$f = f_0 + \varepsilon f_1 + \varepsilon^2 f_2 + \dots \quad \text{interface shape}$$

$$L = L_0 + \varepsilon L_1 + \varepsilon^2 L_2 + \dots \quad \text{period}$$

The functions

$$\mathbf{v}_n, \mathbf{u}_{n+1}, \phi_n, \Psi_n, f_n, L_n$$

are computed in a **perturbation cycle**. f_n & L_n are chosen to satisfy the jump condition for normal stress.

$$\mathbf{v}_0, \mathbf{u}_1, \phi_0, \Psi_0, L_0, f_0$$

are the first cycle; f_0 and L_0 define the domain of the solution at higher orders.

First Cycle: Assume a domain \tilde{f}, \tilde{L} and solve the following two problems:

$$\text{water} \left\{ \begin{array}{l} \rho \mathbf{v}_0 \cdot \nabla \mathbf{v}_0 = -\beta \mathbf{e}_z - \nabla \phi_0 + \mu_w \nabla^2 \mathbf{v}_0, \\ \quad \quad \quad \text{div} \mathbf{v}_0 = 0 \\ \mathbf{v}_0 = 0 \text{ on } r = \tilde{f}(z) \\ \mathbf{v}_0 = -c \text{ on } r = R_z \\ \mathbf{v}_0, \phi_0 \text{ are } \tilde{L} \text{ periodic} \end{array} \right.$$

$$\text{oil} \left\{ \begin{array}{l} 0 = -\beta \mathbf{e}_z - \nabla \Psi_0 + \mu \nabla^2 \mathbf{u}_1, \text{ div} \mathbf{u}_1 = 0 \\ \mathbf{v}_1 \cdot \tilde{\mathbf{n}} = 0 \text{ on } r = \tilde{f}(z) \quad \text{normal component of velocity} \\ \tilde{\boldsymbol{\tau}} \cdot \mathbf{D}[\mathbf{u}_1] \cdot \tilde{\mathbf{n}} = \overset{\circ}{\gamma}_0(\tilde{f}, z) \quad \text{shear rate is prescribed} \\ \mathbf{u}_1, \Psi_0 \text{ are } \tilde{L} \text{ periodic} \end{array} \right.$$

The normal stress conditions. The viscous component of the normal stress vanishes on a rigid solid; $\tilde{\mathbf{n}} \cdot \mathbf{D}[\mathbf{v}_0] \cdot \tilde{\mathbf{n}} = 0$.

$$(A) \quad \begin{array}{l} -\phi_0 + \Psi_0 - \mu_w \tilde{\mathbf{n}} \cdot \mathbf{D}[\mathbf{u}_1] \cdot \tilde{\mathbf{n}} = \frac{\sigma}{\tilde{f}(1+\tilde{f}'^2)^{\frac{1}{2}}} \\ -\tilde{f}'' / (1 + \tilde{f}'^2)^{\frac{3}{2}} \end{array}$$

Iterate \tilde{f}, \tilde{L} until (A) is satisfied giving f_0 and L_0

Remarks:

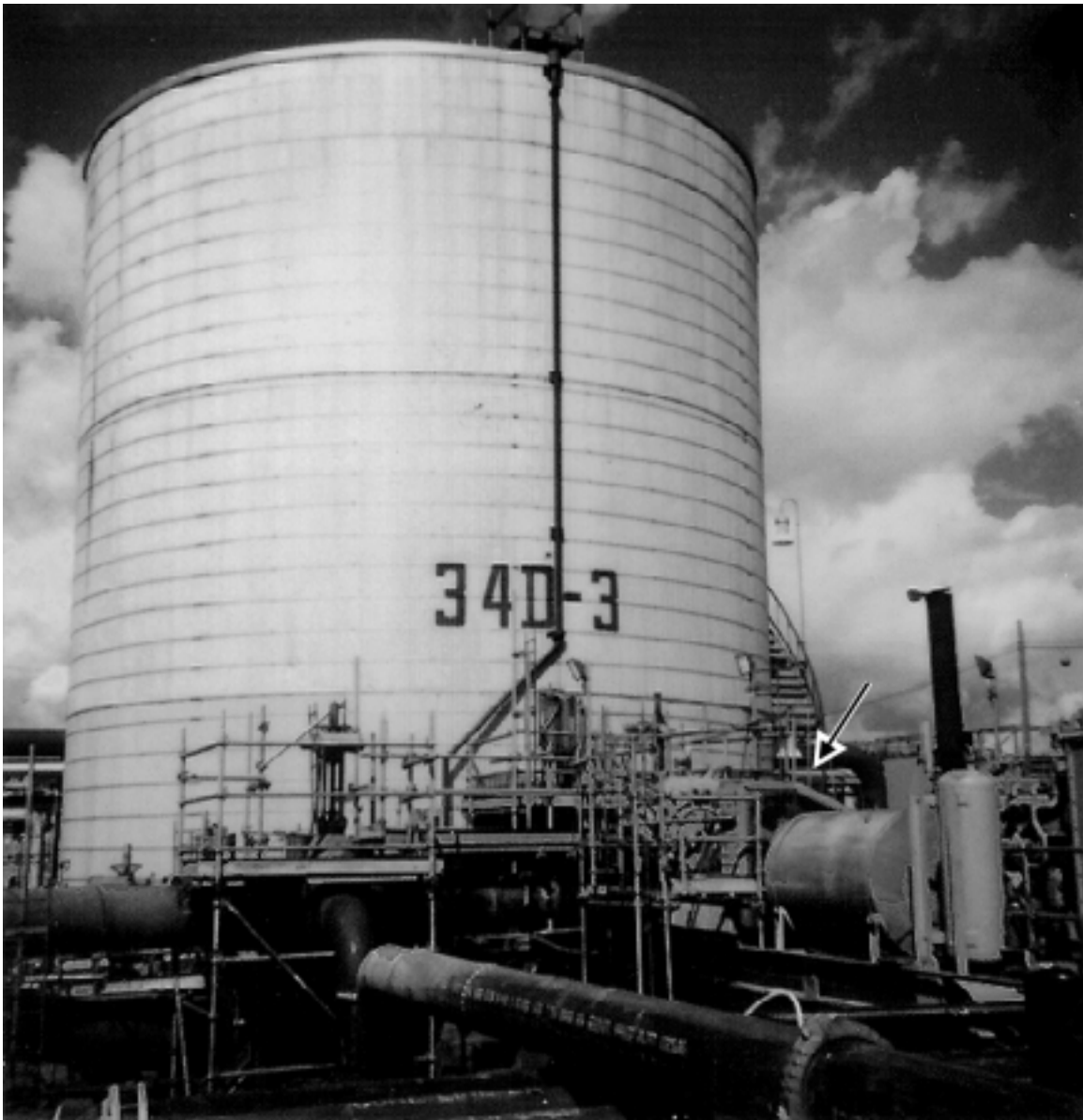
- The problems are decoupled
- f_0, L_0 determine the domain of the solution at all higher orders
- The problems are all decoupled. They are all Dirichlet problems with prescribed interface conditions from previous orders
- f_n and L_n are needed to complete the solution in the n^{th} cycle.
- Rigid deformable core approximation

$$\nabla \Psi_0 = 0, \mathbf{u}_0 = 0$$

This works well, but not perfectly well

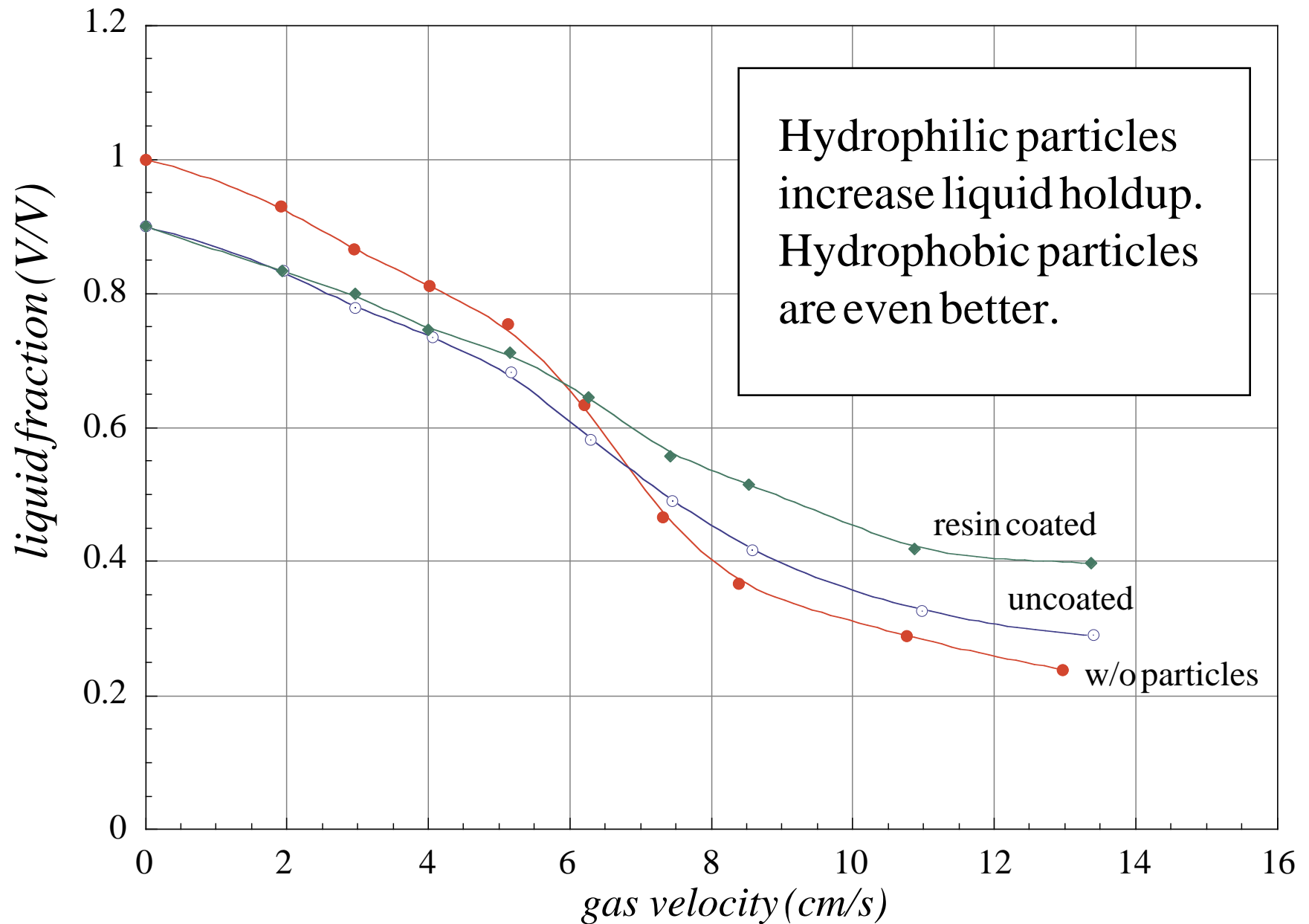


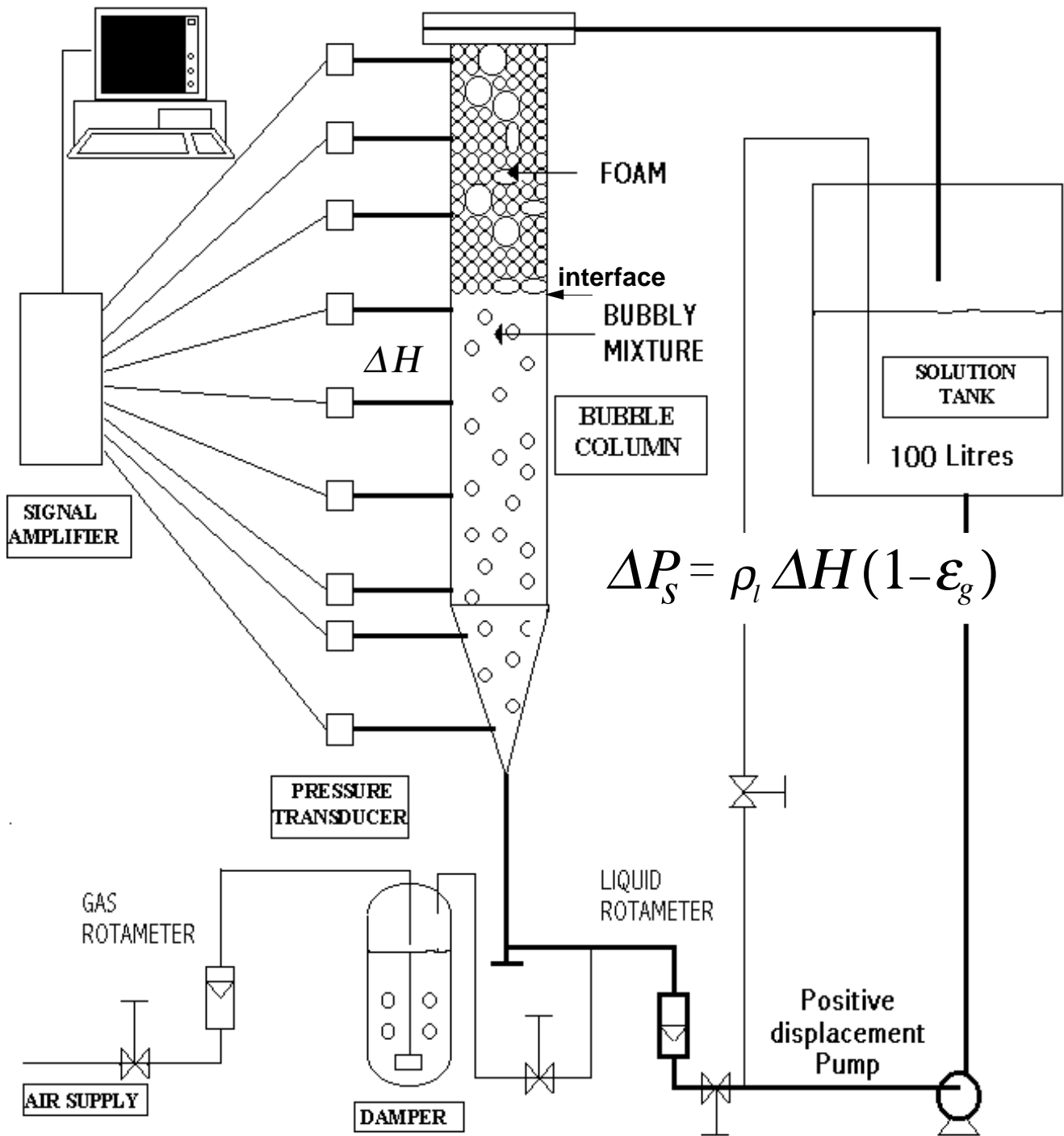
R. Bai & D.D. Joseph next to the 24" Pipeline pilot at the oil sands in Fort McMurray



Froth tank and centripetal pump
at the pilot pipeline

RESIN COATED ($U_l = 0.411 \frac{\text{cm}}{\text{sec}}$)b 10% solids





Slit Reactor:

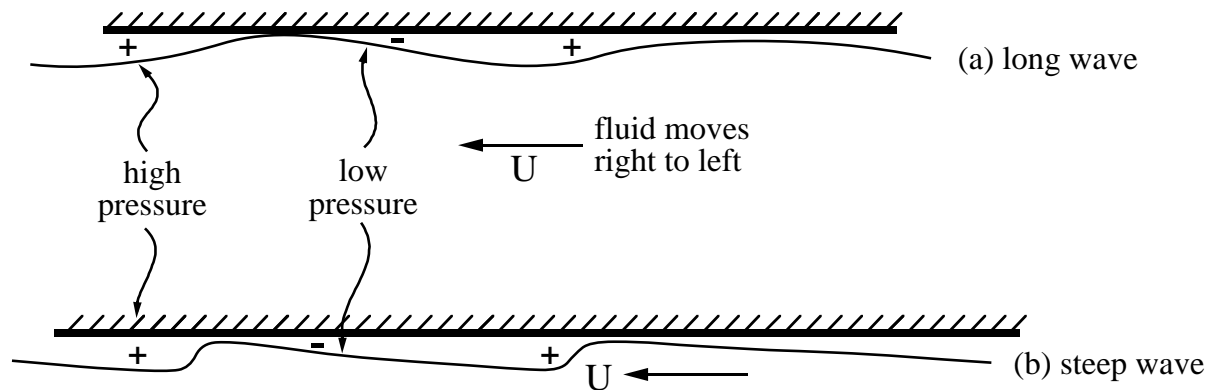
Height 170 cm
 Width 26 cm
 Depth 1.3 cm

Liquid & Gas are injected continuously.
 Flow friction is negligible.
 Can measure ϵ_{gf} , ϵ_{gb} , ϵ_g

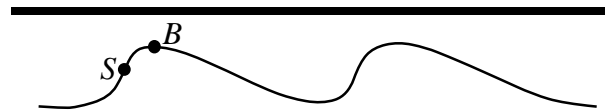
STEEP WAVES

When fluid flows through a gap defined by a wave crest and a solid wall, the pressure at the wave front is much larger than at the rear. This leads to wave steepening at the front side of the wave. This kind of wave steepening appears to be ubiquitous, not only in lubricated transport but also in material processing.

Instability of long waves



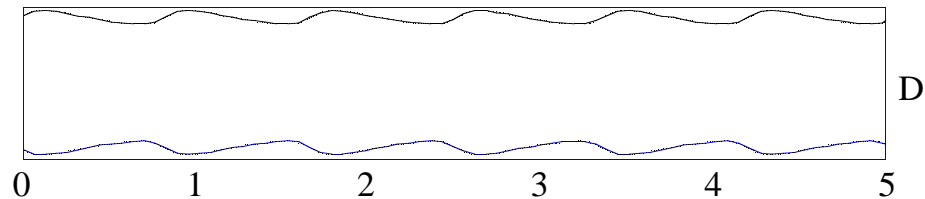
The wave front (a) steepens (b) due to high pressure at the front.



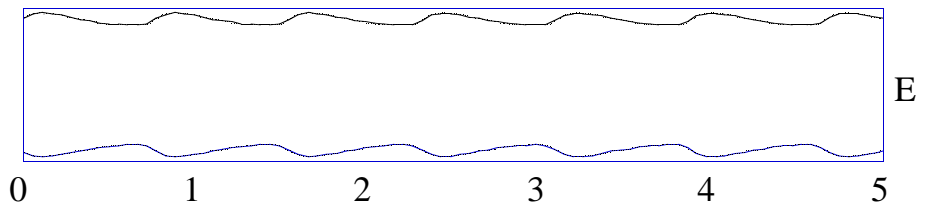
S - Stagnation point pressure
B - Bernoulli pressure

$p_S - p_B$ is important
 high low

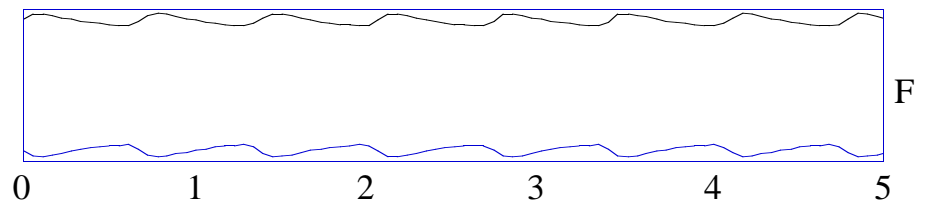
WAVE STEEPENING AND REYNOLDS NUMBER



Re = 420



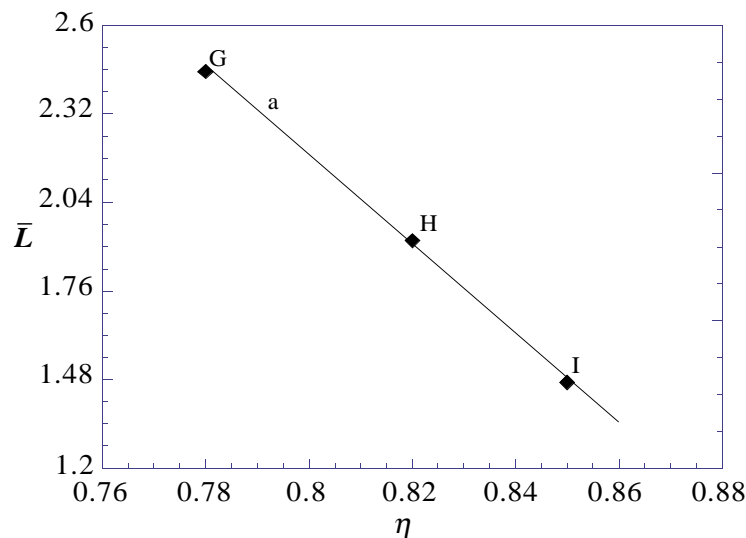
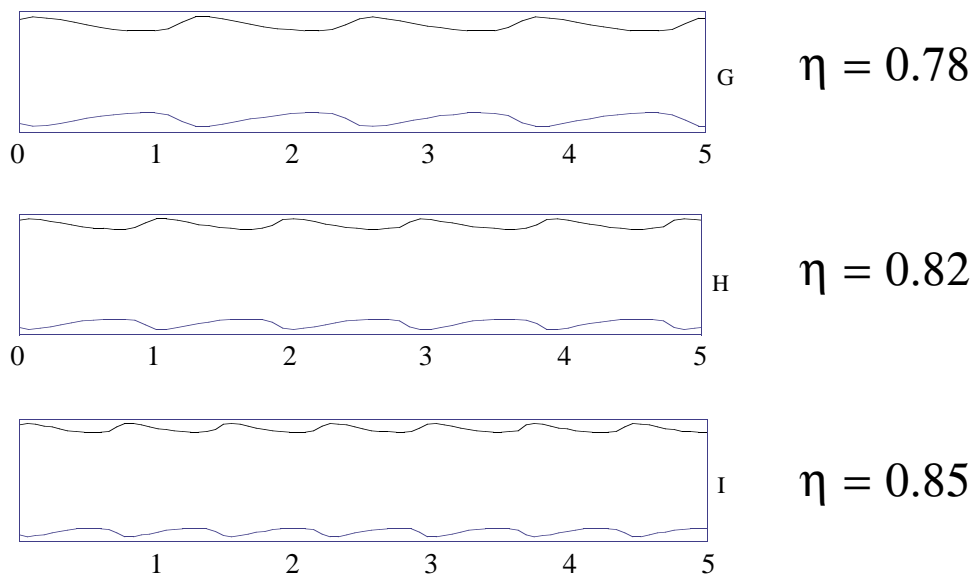
Re = 525



Re = 840

Numerical calculation of BKJ (1996) for $[\eta, h] = [0.86, 1.4]$. The wave length shortens and the wave front steepens as the Reynolds number is increased.

Wave shortening and “sharkskin”



Numerical calculation of BKJ (1996). Wavelength $\bar{L} = 13.5 - 14.1\eta$ for $(\mathbb{R}, h) = (600, 1.4)$. **The wavelength and amplitude tend together to zero as $\eta \rightarrow 1$.** (see JBCR 1997)

Steep waves in annular flows

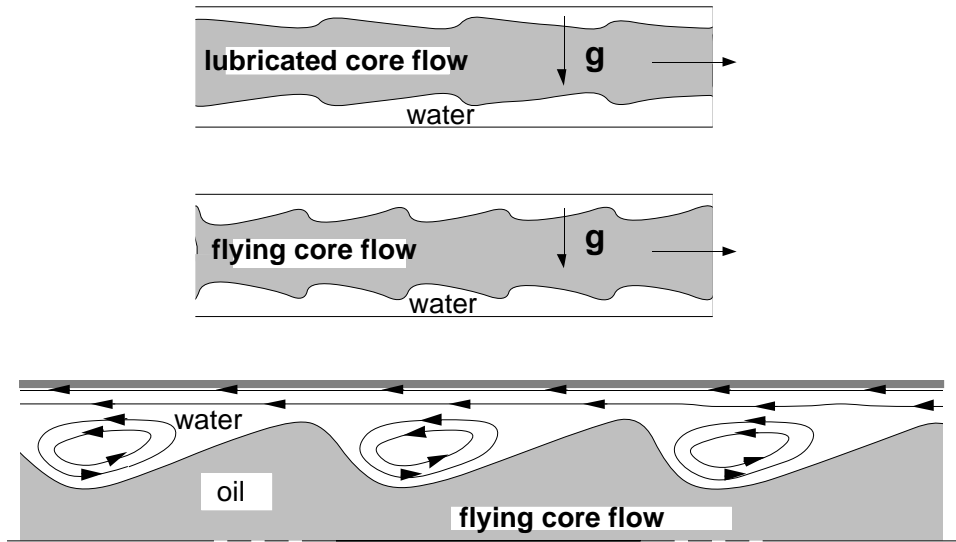


Figure 15: (FHJ 1995) (*top*) The interface resembles a slipper bearing with the gentle slope propagating into the water; the shape of these waves is unstable. (*middle*) The high pressure at the front of the wave crest steepens the interface and the low pressure at the back makes the interface less steep. (*bottom*) The pressure distribution in the trough drives one eddy in each trough. The waves in (a) are unstable and lead to (b). To get a lift from this kind of wave it appears that we need inertia, as in flying. Liu's [1982] formula for capsule lift-off in a pipeline in which the critical lift off velocity is proportional to the square root of gravity times the density difference is an inertial criterion. Industrial experience also suggests an inertial criterion, since CAF in the Shell line could be maintained only when the velocity was greater than 3 ft/s; at lower velocities the drag was much greater.

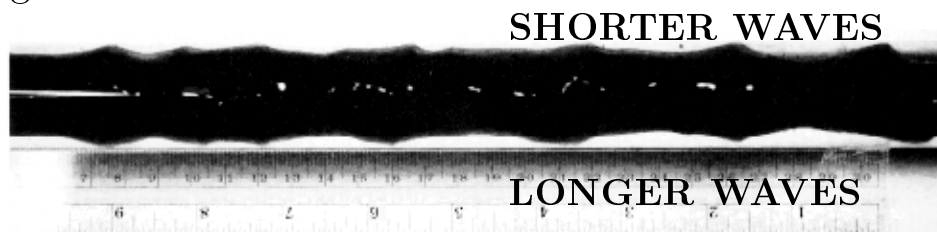


Figure 16: (J 1997). Core annular flow of #6 fuel. The saw-tooth waves on the oil core in a horizontal pipeline. The flow is from left to right.

CONDITION FOR LUBRICATION

- Water will go to the pipe wall if the oil viscosity is larger than about 5 poise.

ENERGY SAVING

- Drag reductions of the order of the viscosity ratio are possible

$$\mu_0/\mu_w = 1000/\frac{1}{100} = 10^5$$

INDUSTRIAL APPLICATION

1906 Isaacs and Speed proposed to rifle the pipe and throw the water to the wall by centripetal acceleration

1930's Various oil companies built short pilot lines, a few miles

1960's Canadian studies at Alberta by Govier, Hodgson, Charles

1970 - 1982 Shell ran a commercial 8" line from Bakersfield to the upgrading facility at ten section. Ran especially well when using produced water, but you got lubrication only for flow velocities

$$U > 3 \text{ ft/sec}$$

You need inertia to levitate the flow

1996 Syncrude froth pilot: This is a 1 km long 24" pipe. You get self-lubrication rather than lubrication because the water is already there. The water is a colloidal dispersion of clay which promotes the self lubrication. Additional water is not added.

FLOW TYPES

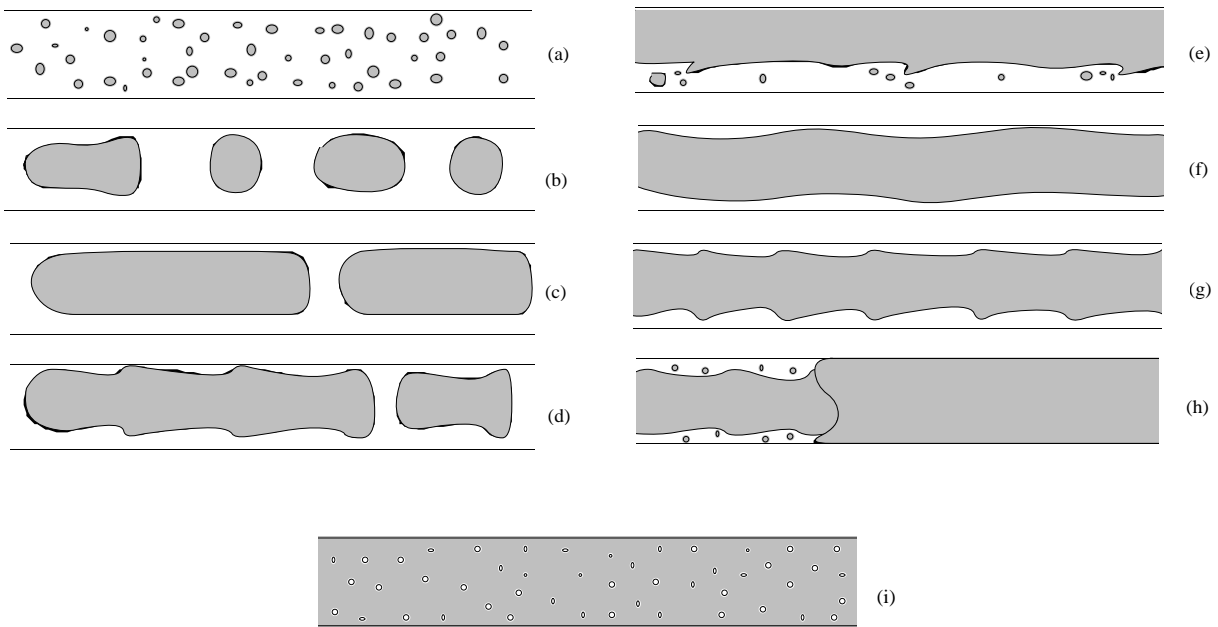
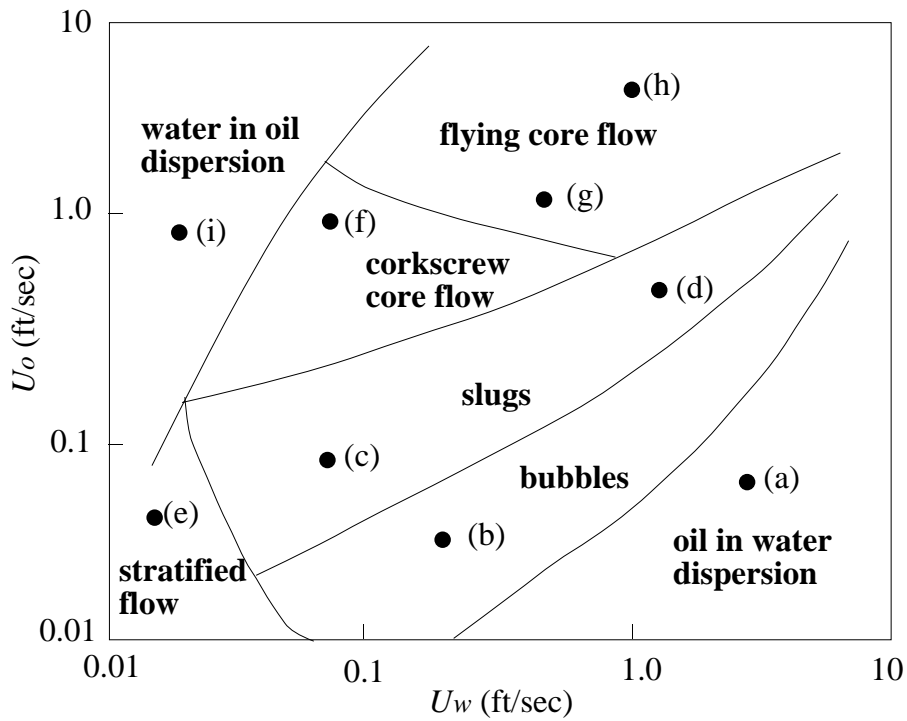


Figure 1: (JBCR 1997) Cartoons of a flow chart and flow types in horizontal flow when the oil is lighter. The flow is from right to left. All flows but (e) and (i) are lubricated. The holdup ratio $h = \bar{U}_0 / \bar{U}_w$ where \bar{U}_0 is the average oil velocity and \bar{U}_w is the average water velocity. $h = 1$ for finely dispersed flow like (i), $h = 2$ for perfect core flow, $h \approx 1.5$ for wavy flow.

STEEP WAVES IN GAS LIQUID FLOW

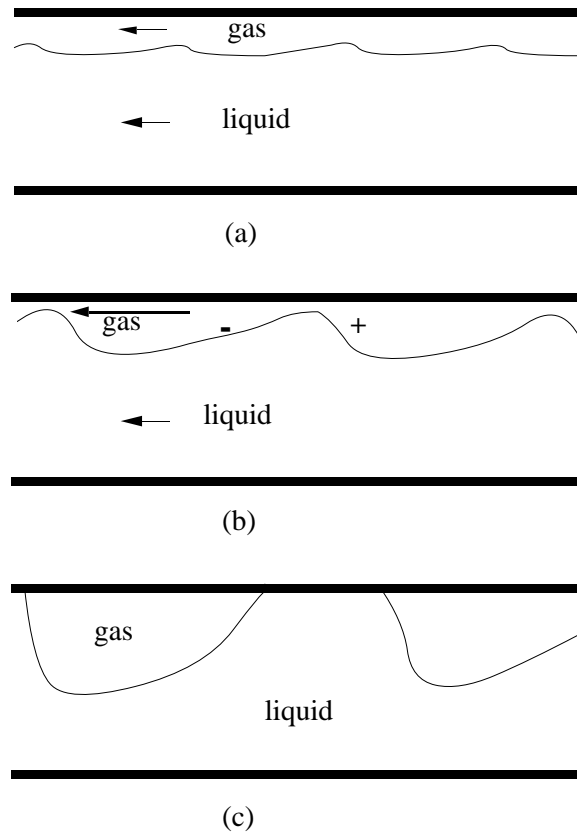


Figure 12: (JNB 1996) Slugging in gas-liquid flow. The high pressure at the front side steepens the wave and the low pressure at the back side smooths it. If the amplitude of the wave is large enough it will touch the wall. Bernoulli effects can also suck the liquid to the wall when the gas velocity is large. Note that we have avoided drawing the ripples and small roll waves which are probably always superimposed on the gas-liquid interface. We focus on macro-structures.

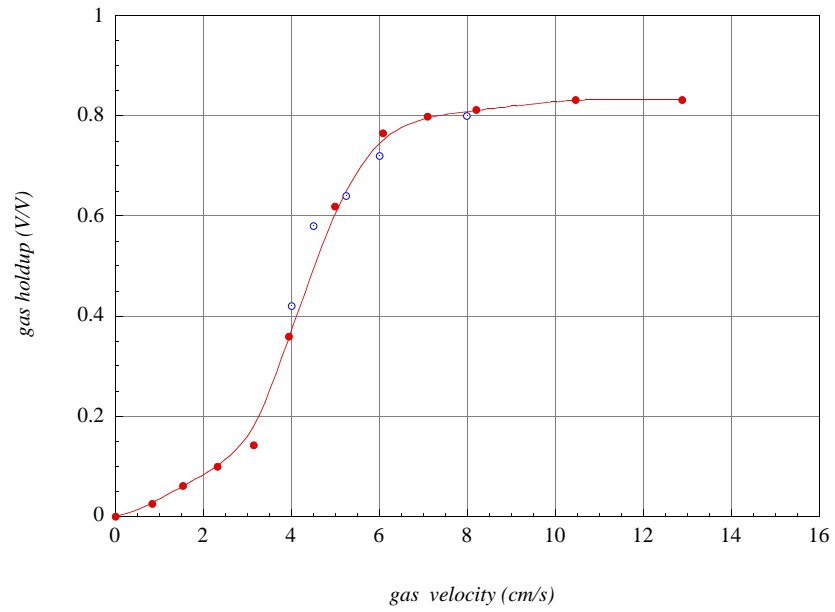


Figure 1. Gas holdup as a function of gas velocity, for a 0.06% wt. SDS + 1.0% wt. 1-Butanol solution at a liquid velocity of 0.154 cm/s (solid circles) and the CANMET process, which liquid velocities are in the range 0.1 - 0.2 cm (open circles).

Self Lubrication of bitumen froth

What is bitumen froth?

Production of froth

Clay water

Neiman's experiments at Syncrude's experimental facility (1985)

2" × 47 meter pipeloop

“Pipelining of froth in the syncrude expansion case may be technically and economically feasible”

Did not investigate fouling, restart temperature effects or mechanism for self-lubrication. No scale-up results.

Syncrude's pipeline problem

Dilution, heating or self-lubrication

SCALE UP EXCLUDING NIEMAN'S DATA. THE PRESSURE GRADIENT IS 10-20 TIMES GREATER THAN THAT FOR WATER ALONE

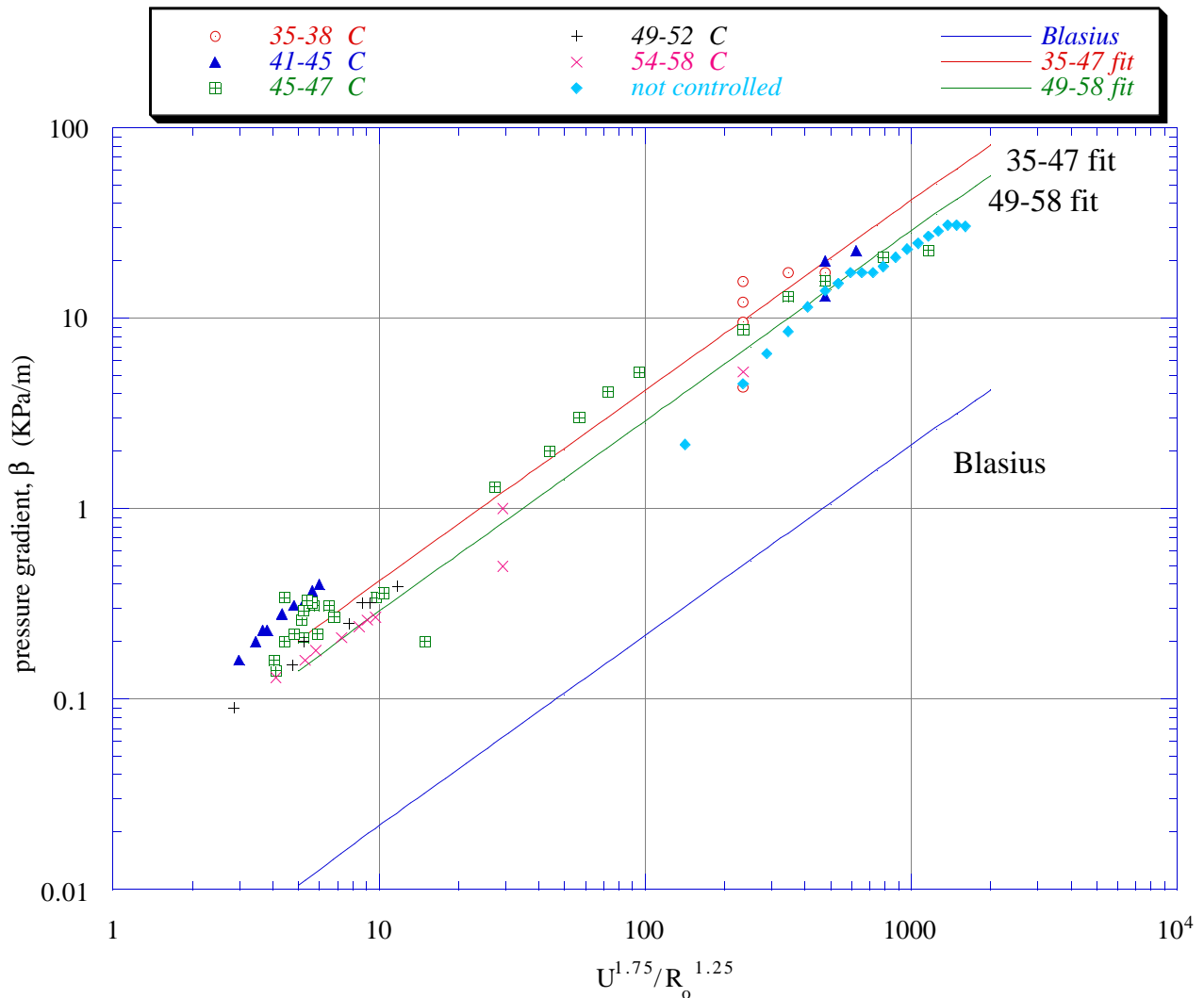
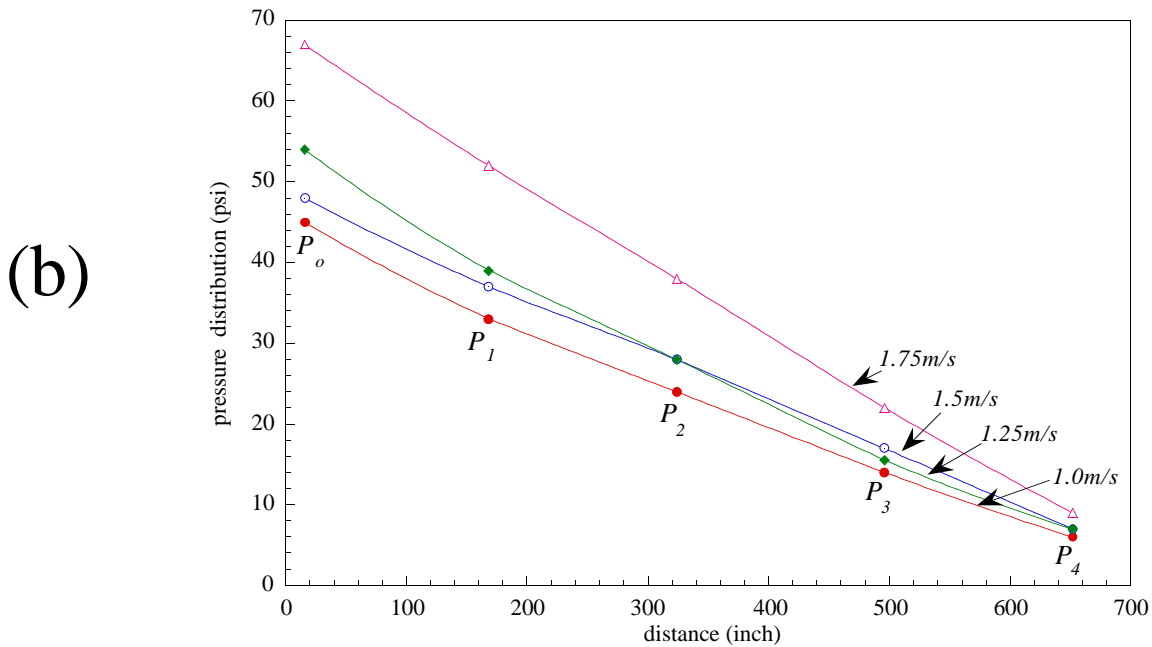
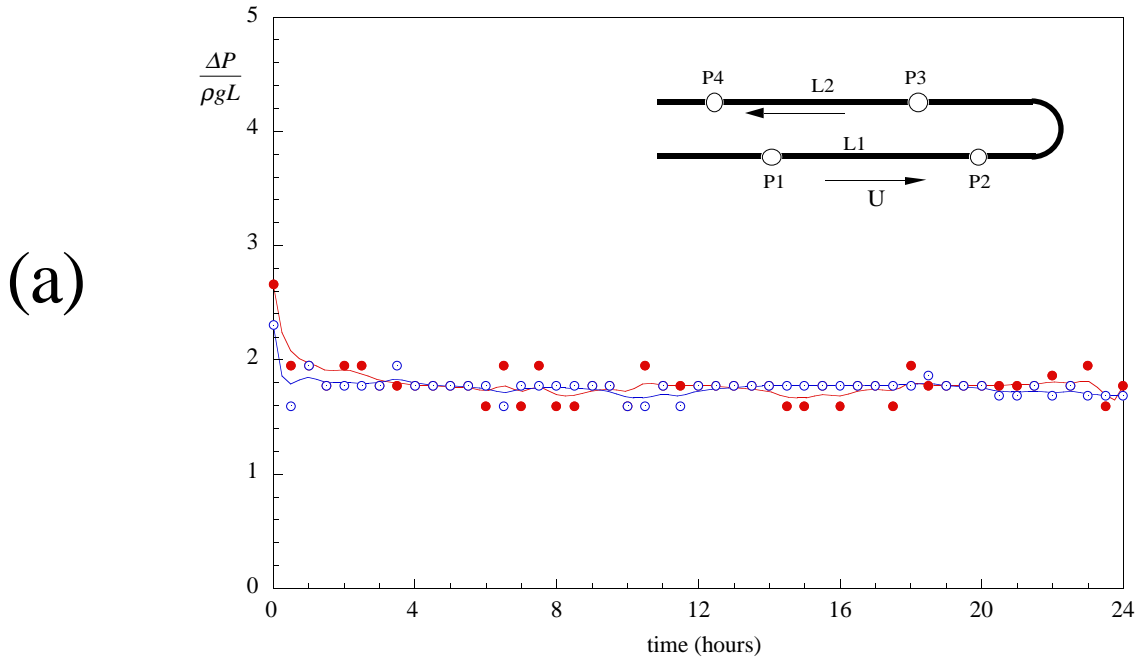


Figure 4.2. Fittings parallel to the Blasius correlation for turbulent pipeflow (bottom line), for two temperature ranges: 35-47 °C (top) and 49-58 °C (middle) presented in figure 4.1. Most of the 2''(50 mm) diameter pipeline data was ignored in these fits, due to its high scatter.

MINNESOTA EXPERIMENTS, 1" × 250"

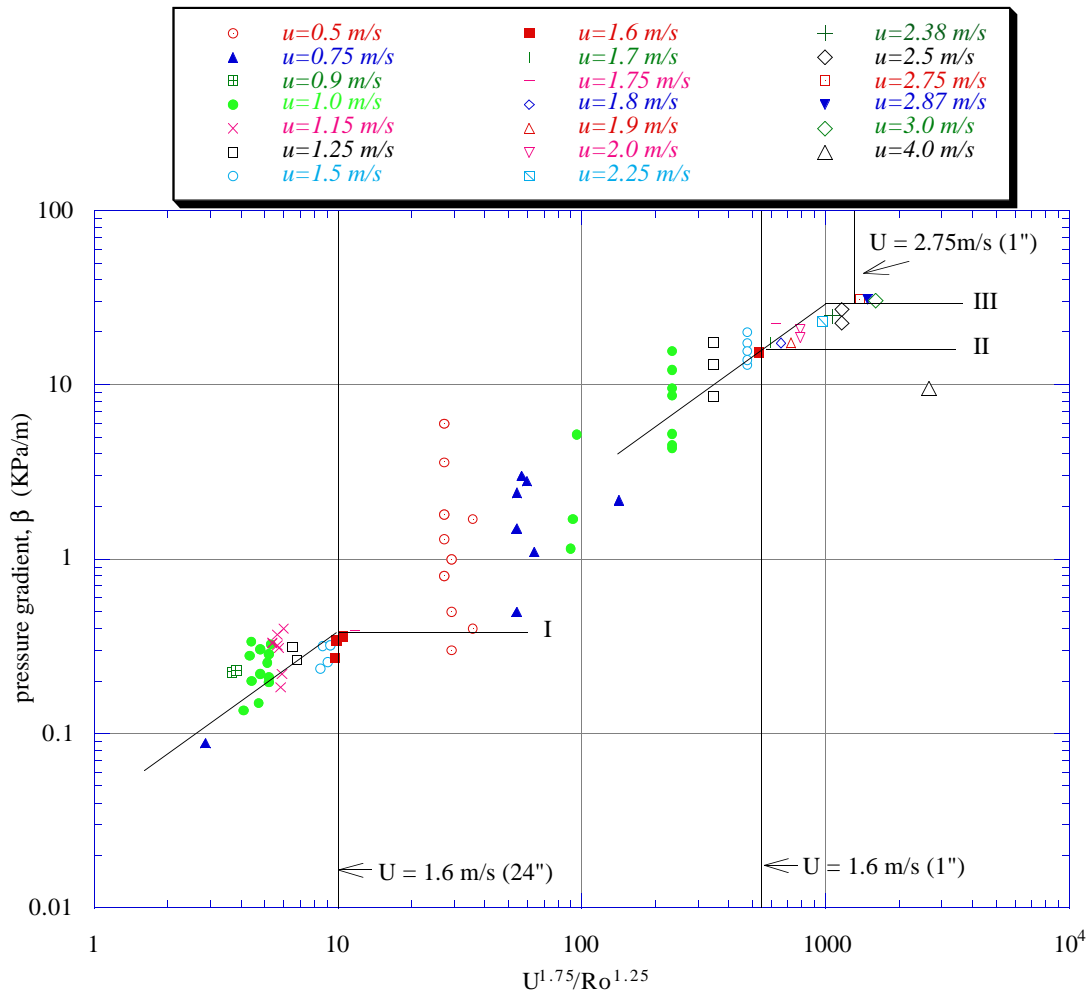
- Mechanism of self-lubrication
- Powdering the dough
- Critical velocity (shear stress) for start up
- Tiger waves

NO BUILDUP OF FOULING IN 96 HOURS



(a) Dimensionless pressure gradient $\Delta P/L\rho g$ history between two consecutive pressure taps in the forward \bullet and return \circ legs of the pipeline for test 3 (b). $L_1=L_2=3.96$ m. In this case, $\Phi=27\%$, $U=1.5$ m/s and $\theta=37^\circ\text{C}$. (b) Pressure distribution along the pipeline, parametrized by the velocity U for test #3, 96 hours. P_o is the pressure at the pump outlet and P_1, P_2, P_3, P_4 are located on the line, so P_1 corresponds to the tap closest to the pump and P_4 is the most distant. In this case, $\Phi=27\%$ and θ varied from 35°C , for $U=1.0$ m/s to 42°C , for $U=1.75$ m/s.

PRESSURE GRADIENT SORTED BY VELOCITY. SUPER LUBRICATION, “SOMETHING FOR NOTHING”



(b)

Figure 4.3 Pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by velocity. Left: 24”(0.6m) diameter pipeline; middle: 2” diameter pipeline (Niemans’ data); and right: 1” diameter pipeline. (a) All available data, enclosed by the most pessimistic (i) and least pessimistic (ii) predictions for β based on Blasius’ formula, and ignoring the scatter in the 2”(50 mm) diameter pipeline data region. (b) I and II and III are predicted pressure gradients β , based on a velocity criterion, for the 24”(0.6m) diameter pipeline data and 1”(25 mm) diameter pipeline data, respectively. Here the critical velocity is approximately $U_c = 1.6$ m/s for curves I and II and $U_c = 2.75$ m/s for curves III.

FRICIONAL HEATING AND BLASIUS SCALE UP, “SOMETHING FOR NOTHING”

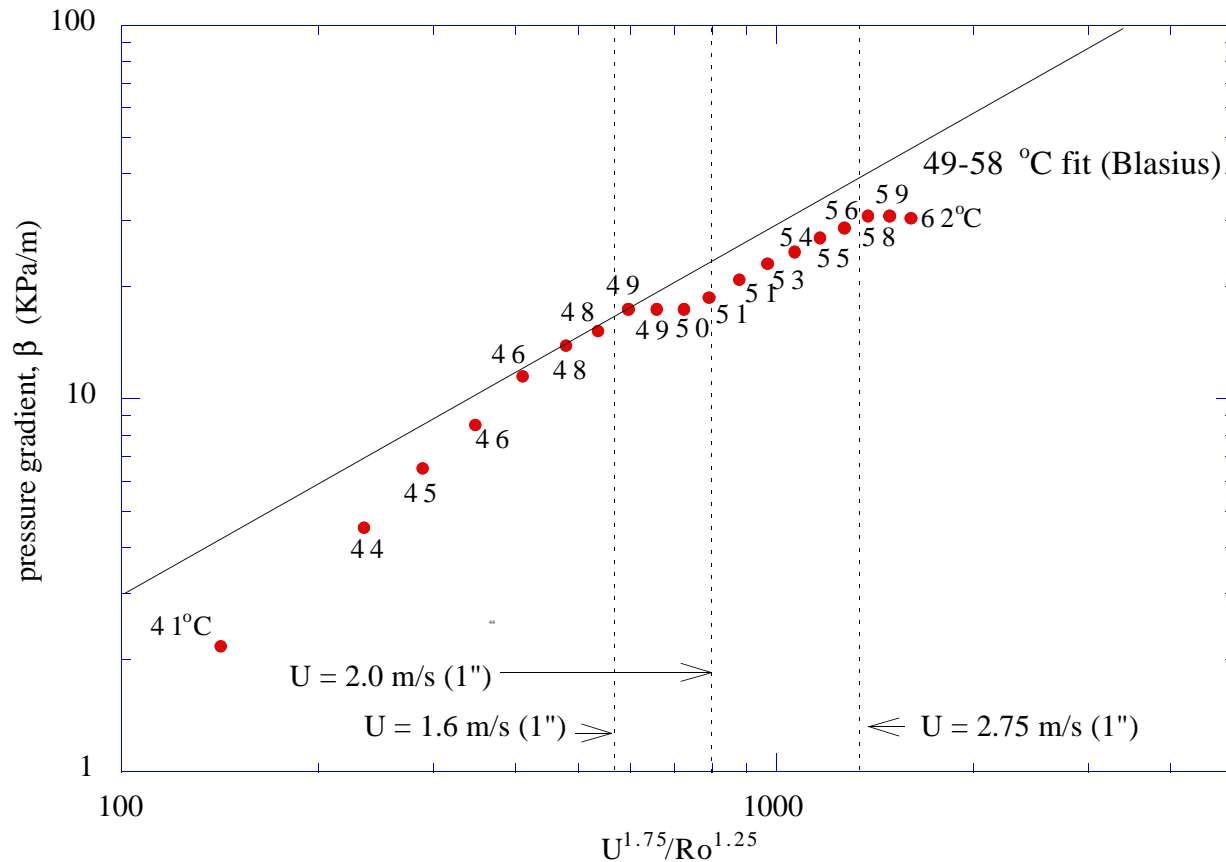


Figure 4.4 Pressure gradient vs. Blasius parameter in the 1” (25mm) diameter pipe. The temperature of the room was 26°C and the froth temperature was not controlled; the increase in temperature is due to frictional heating as shown in figure 4.5.

FRICIONAL HEATING

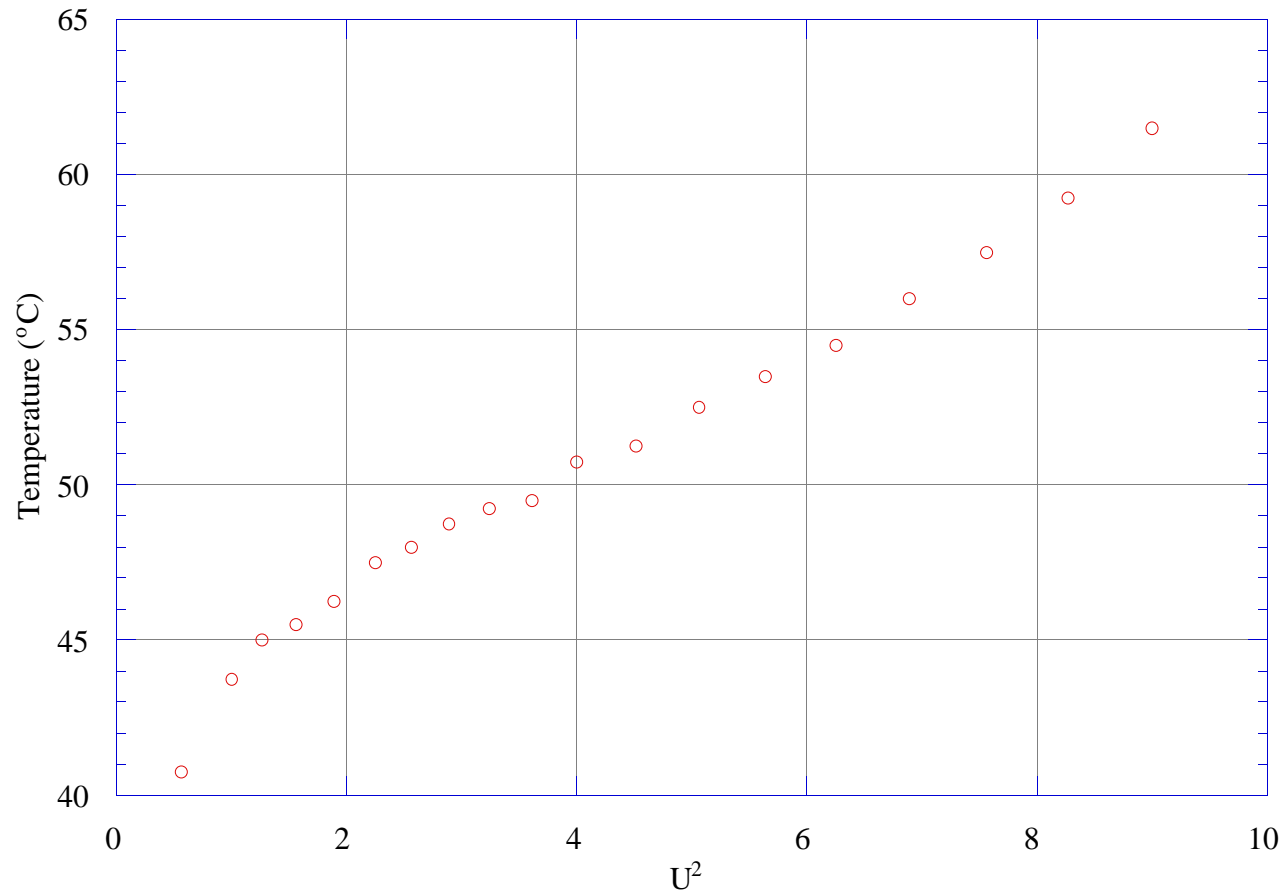


Figure 4.5 Temperature vs. the square of the flow speed for conditions specified in figure 4.4; the rise in temperature is approximately linear suggesting frictional heating.

LOSS OF LUBRICATION AS A FUNCTION OF TEMPERATURE

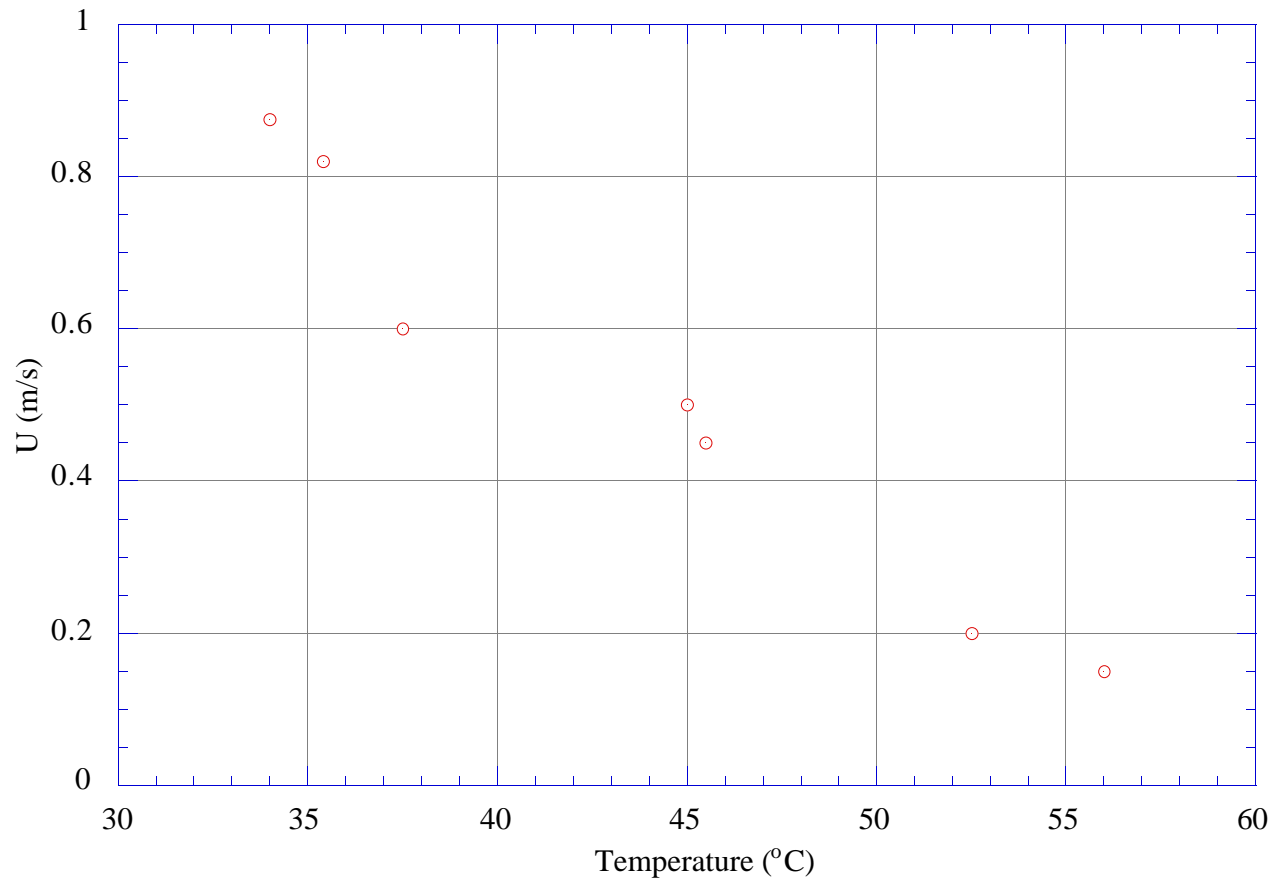


Figure 4.6 Froth velocity at which self lubrication is lost as a function of the froth temperature. Self lubrication is more persistent at high temperatures.

SCALE UP
WITH
BLASIUS
LAW
SORTED BY
TEMPERA-
TURE

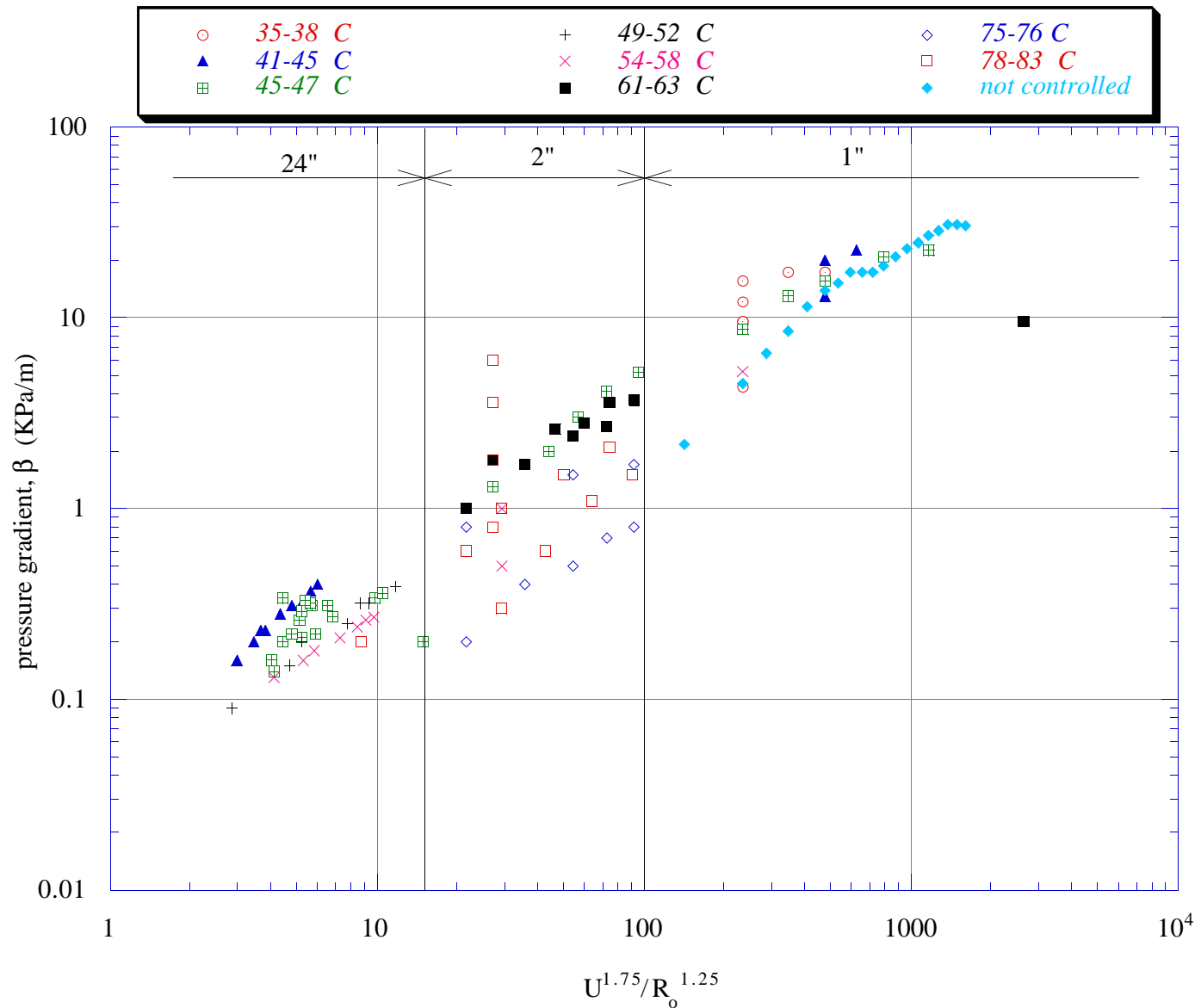


Figure 4.1 All available data for pressure gradient of bitumen froth β [Kpa/m] as a function of the ratio of the 7/4th power of the velocity to the 4/5th power of the pipe radius, parametrized by temperature. Left: 24”(0.6 m) diameter pipeline; middle: 2”(50mm) diameter pipeline (Niemans’ data); and right: 1”(25 mm) diameter pipeline.

Hydrophobic particles suppress foam and increase liquid holdup better than hydrophilic particle.

We believe that hydrophobic particles suppress foam in the same way as hydrophilic particles, but in addition act to collapse the foam at the interface between the foam and bubbly mixture.

CRITICAL CONDITIONS FOR FOAMING

There are two important properties of foam:

- (1) foaminess which is like the height of head of foam after depressurization or agitation
- (2) stability of foam which is how fast the head collapses. Champagne gives rise to large heads of foam as do beers, but champagne heads collapse more rapidly.

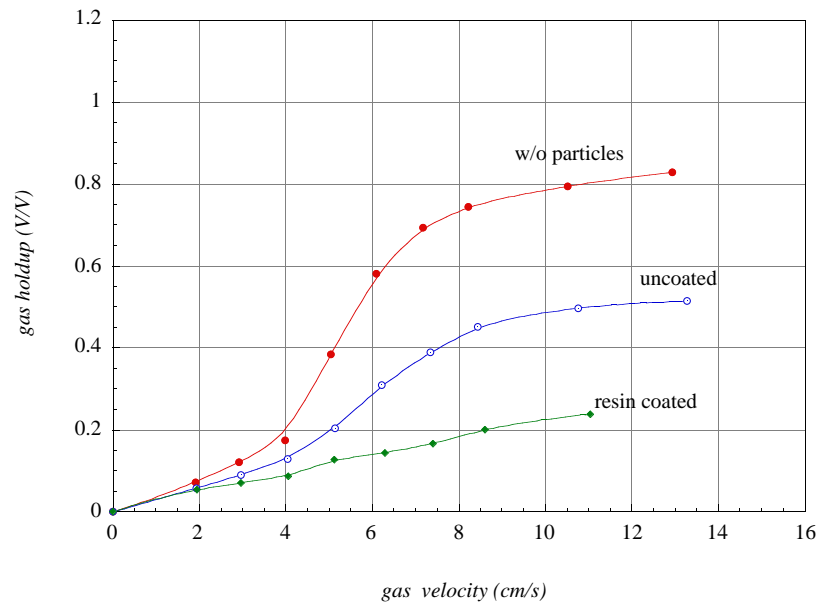
In our foaming reactor we get foam when the gas velocity is larger than critical. In beer you need to create a critical condition in terms of the rate and magnitude of depressurization.

SYNCRUDES PILOT STUDY (1996)

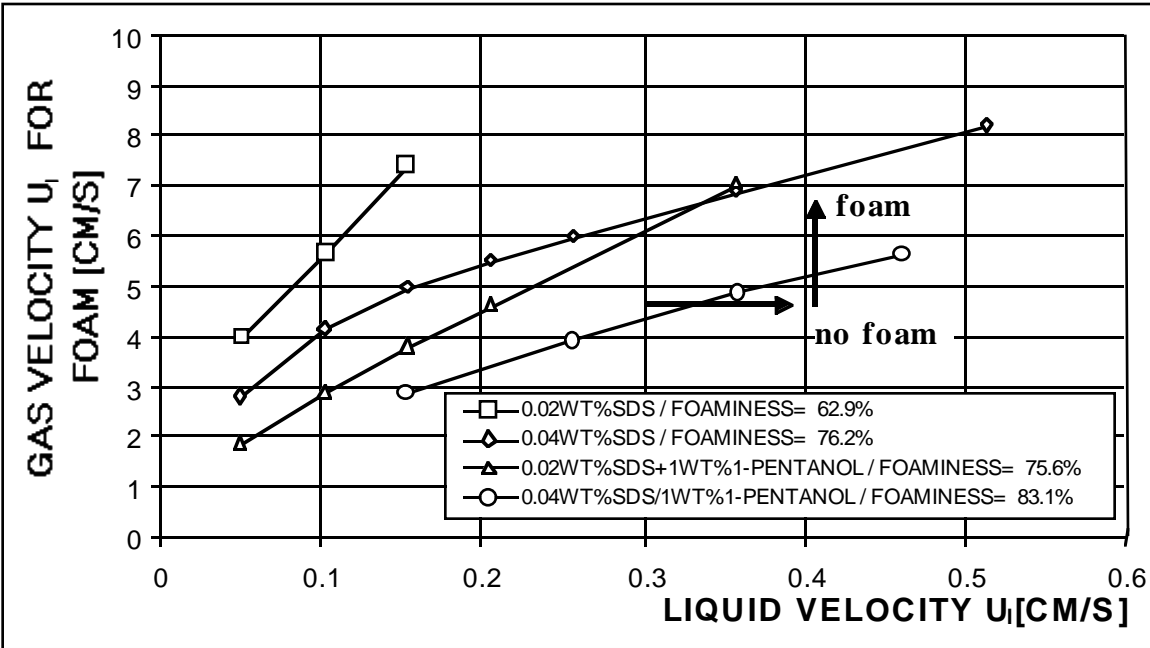
24" × 1000 meter pipeline
(oil sands in Fort Mc Murray)

They obtained results consistent with
the Minnesota and Neiman
(2" pipeline) studies

The results from the 24" pilot pipeline allowed
us to establish the scale up law



Gas holdup as a function of gas velocity



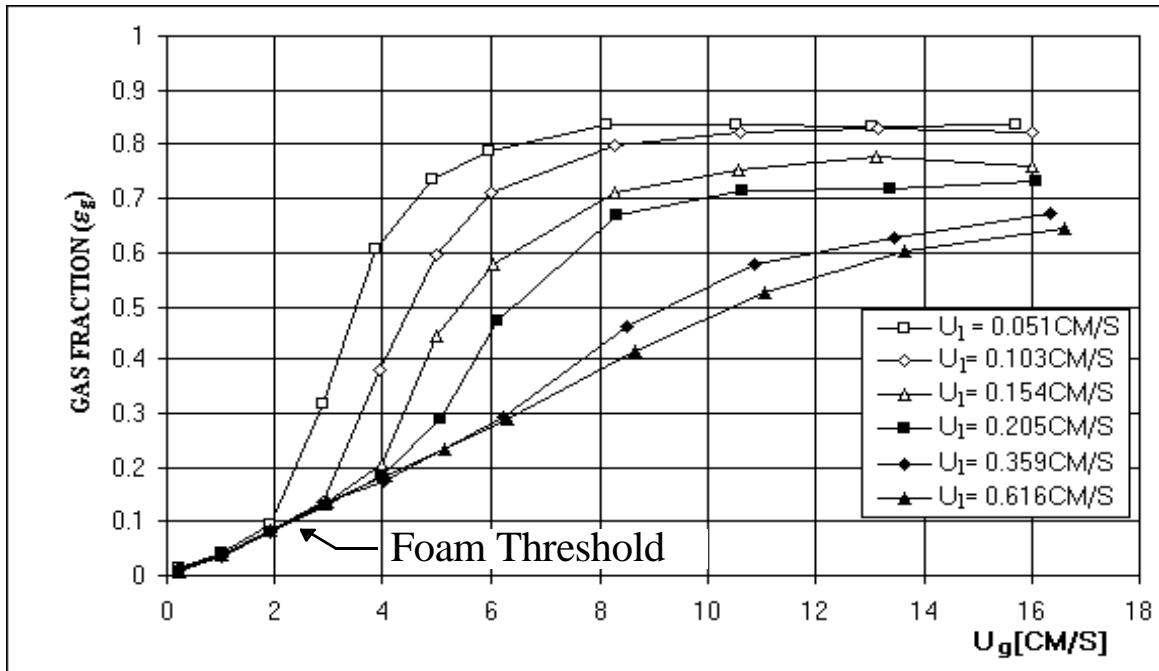
FOAM THRESHOLD

$$U_g = a + bU_l$$

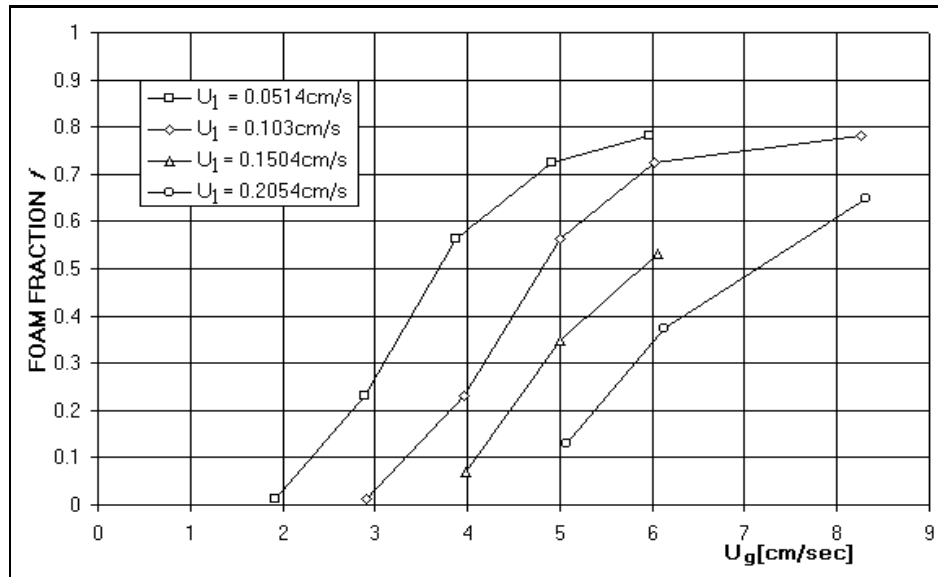
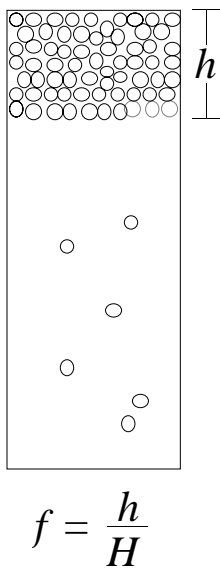
a, b are independent of velocity
but depend on the surfactant

Beer, champagne, foamy oils foam when depressurized. The release rate of gas bubbles (equivalent to U_g) must be above a threshold.

GAS FRACTION AND FOAM FRACTION



Gas fraction as a function of gas:Water/0.02wt%SDS/1 wt% 1-Pentanol.



Foam fraction f as a function of gas velocity:
Water/0.02wt%SDS/1 wt% 1-Pentanol.

- Most of the gas in the reactor is in the foam. You can get a little over 80% gas.

SOME RESULTS

- The gas fraction decreases and the liquid fraction increases with batch volume fraction of particle
- Plastic is lighter and suppresses foam better than glass
- The greater the wetted area of solids, the more effective is the suppression of foam

EXPLANATION

- The basic fact is that hydrophilic particles don't fluidize in foam. Foaming may be strongly suppressed by fluidizing hydrophilic particles in the bubbly mixture below the foam. The suppression is achieved by increasing the liquid hold-up by bed expansion; by increasing the wetted area of solid surface (walls and particles); and by decreasing the gas hold-up by increasing the effective density of the liquid-solid mixture.

TWO PHASE FLOW MODELS (MIXTURE THEORY, LNS) DO NOT PREDICT:

- Long bodies stable broad side on
- Drafting, Kissing, and Tumbling
- Across the stream arrays of spheres
- Nested wake structure, “Flying Birds”
- Doublets, Triplets, Quadruplets
- Fluidized Raft, Wake Aggregates

TWO PHASE FLOW MODELS FOR VISCOELASTIC FLUIDS ESSENTIALLY DO NOT EXIST