

Figure 3.12b. Time evolution of the reaction surface; $Z=0$, $\beta=10000$.

Presented examples explain the role of deformation in mixing on the molecular scale: generation of an intermaterial area, decreasing of segregation scale, increasing of concentration gradients and the relation between stretching and orientation.

Growth of concentration gradients is observed in the direction of contraction, whereas their decline is observed in the direction of stretching. This observation is useful for modelling of micromixing, as it allows in many cases to consider mixing on the molecular scale as one-dimensional process.

It should also be pointed out that stretching of liquid elements tends to stabilize the penetration distance of the diffusive solutes. The time necessary to stabilize the profile is of the order of $t_{E1/2}$ and the shape of the limiting profile depends on the stretching geometry and the ratio of the constants for deformation and diffusion.

3.2. Effects of Physical Properties of Mixed Media on the Course of Mixing.

Laminar mixing can be strongly influenced by physical properties of mixed liquids. This influence takes different forms in single-phase and multi-phase systems. Mixing of multi-phase systems generally is not considered in this thesis; some information about two-phase liquid-liquid systems seems to be necessary for comparison.

There is a strong evidence in the literature [34,50,53,54] that mixing of immiscible or partially miscible liquids usually results in dispersion of the minor component into droplets (though there are examples that the minor component forms a continuous phase [68]). The primary reason for break-up of the minor component striations or filaments into drops is interfacial tension. Interfacial tension, σ , is responsible for discontinuity of the normal stress, $\bar{\sigma}$, at the liquid-liquid interface:

$$\vec{\sigma}_d - \vec{\sigma}_c = \sigma \cdot \nabla \hat{n} . \quad (3.50)$$

Symbol \hat{n} in equation (3.50) is a versor normal to the interfacial surface, directed into the continuous phase. The linear theory of stability shows [69,51] that the discontinuity of the normal stresses at the interface is the primary reason of the fact that an infinitely small disturbance of the interface can grow in time. When the scale of disturbance is comparable with the scale of a striation or filament of the dispersed phase, the action of the interfacial tension breaks up these structures into a number of drops. The rate of growth of flow disturbances and their scales depend on [51,53,54]:

- the value of interfacial tension,
- the magnitude of deformation rate,
- differences of viscosity and density of the mixed liquids,
- entrance effects (e.g. the diameter of the feeding pipe).

The phenomena of dispersion in a two-phase system may completely stop reduction of segregation scales and the generation of intermaterial area. A simple extension of models developed for single phase systems to multiphase systems may lead to serious errors.

In the single phase systems the rate of reduction of segregation scales and generation of the intermaterial area can be also affected by differences in viscosity and density of mixed liquids [12,24,28]. When the mixed liquids do not differ in viscosity and density, they are deformed with the same rate. However, when there is viscosity difference, the velocity gradients become discontinuous.

To illustrate this phenomenon let us consider two-dimensional shear flow of two liquids differing in viscosity, as presented in figure 3.13. The condition of continuity of tangential stress - τ_{yx} requires:

$$\mu_c \cdot G_c = \mu_d \cdot G_d , \quad (3.51)$$

where

$$G = \frac{\partial v_x}{\partial y} . \quad (3.52)$$

If $\mu_d < \mu_c$ then liquid "d" is exposed to faster shear than liquid "c" and vice versa. According to Middleman [2], the shear rate - G_d can be calculated from the following expression:

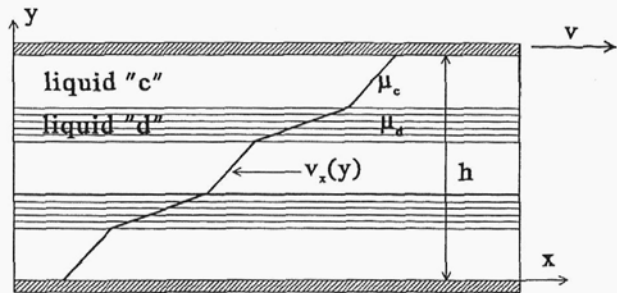


Figure 3.13. Shear flow of layers of alternating viscosity.

$$G_d = \frac{\mu_c}{\mu_d} \cdot \frac{v}{h} \cdot \left[1 + \left(\frac{\mu_c}{\mu_d} - 1 \right) \cdot \phi_d \right]^{-1} , \quad (3.53)$$

where ϕ_d stands for volume fraction of the dispersed liquid in the system. Analysis of this equation shows that for $\mu_c \gg \mu_d$

$$G_d \approx \frac{v}{\phi_d \cdot h} > \frac{v}{h} \quad (3.54)$$

and for $\mu_c \ll \mu_d$

$$G_d \approx \frac{\mu_c/\mu_d}{1-\phi_d} \cdot \frac{v}{h} \ll \frac{v}{h} \quad (3.55)$$

The ratio v/h represents the nominal shear rate in the system.

This simple study clearly indicates that it is more difficult to mix a high viscosity minor component into a low viscosity major component than vice versa. However, a care should be taken when generalizing this suggestion. As indicated by Ranz [28], mixing of liquids widely differing in viscosity may lead to formation of segregated, periodical structures even in completely miscible liquids. These structures result from the flow instability: the reason for instability is the difference in viscosity between liquids or more exactly discontinuity of velocity gradients at the interface. Thus, an assumption that the stable primary flow (as shown in figure 3.13) determines mixing efficiency may be completely wrong. The reason is that the transport of energy from the primary, stable flow to the secondary unstable flows decreases the amount of energy which can induce deformation of liquid elements. Formation of flow instabilities retards the processes of reduction of segregation scales and generation of the intermaterial surface area. One should remember, however, that even when the theory of stability predicts that the unstable flow is possible in the system, the instabilities may not appear in reality. The residence time of liquid elements may simply be shorter than the time scale of growth of flow instabilities. Such a situation may happen in a continuous flow mixer, when the more viscous "minor" component is mixed with the less viscous "major component. Recapitulating the above considerations, it should be stressed that the main mechanisms affecting micromixing in very viscous liquids are: deformation and molecular diffusion in deformed liquid elements. The rate of deformation and consequently the generation of new contact area generation is influenced by orientation of intermaterial surfaces and physical properties of mixed liquids. Interfacial surface tension slows down deformation of liquid elements in the two-phase systems. The effects of viscosity ratio of the mixed liquids are very complex and there is no simple conclusion in this case.

Figure 3.14 shows schematically possible behaviours of dispersed liquid in the system during mixing, depending on physical properties of liquid (this is an extension of the sketch presented by Ottino [60]).

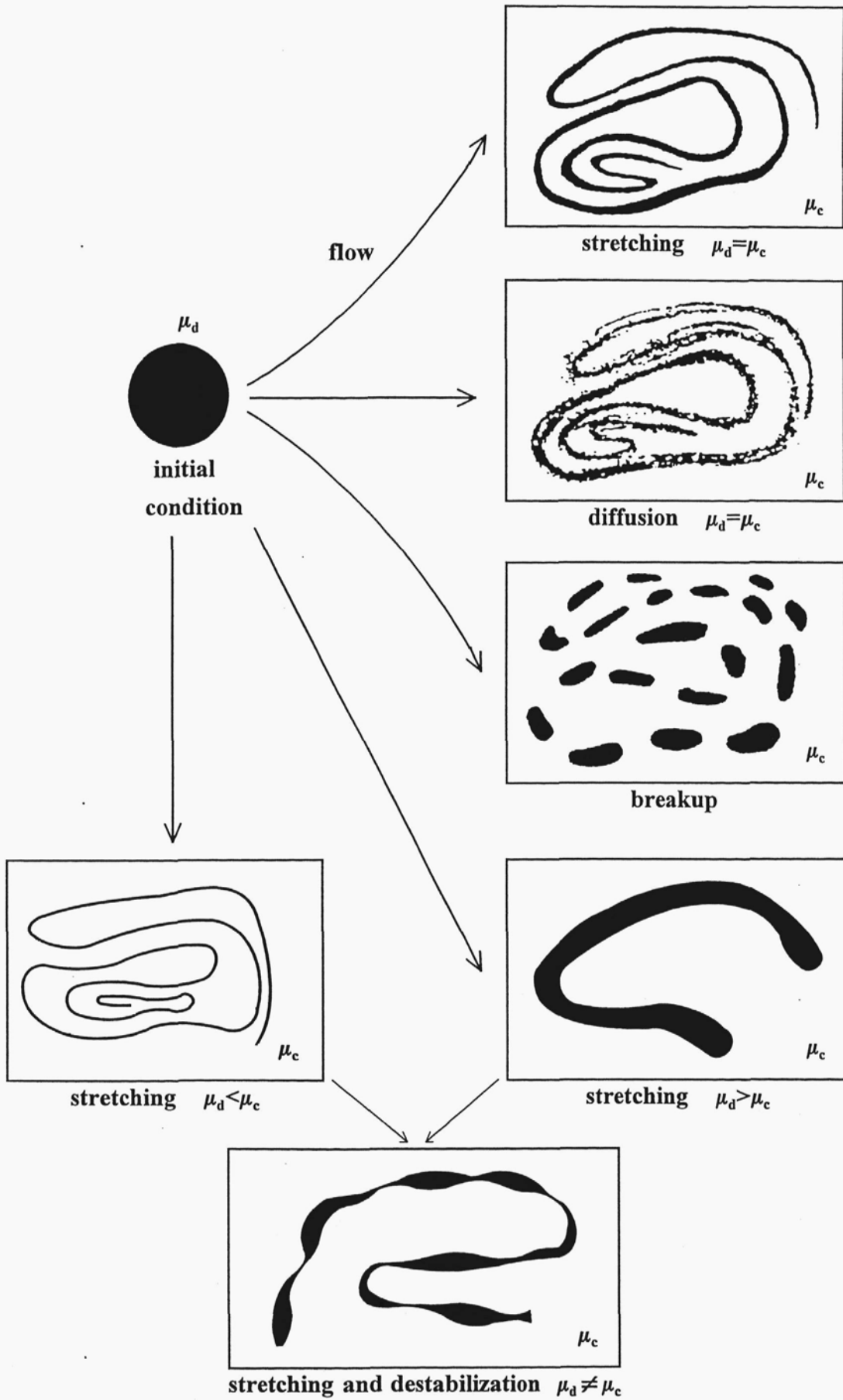


Figure 3.14. Schematic presentation of different phenomena in laminar mixing.