Mixing on Newtonian and non-Newtonian media in Laminar and Transition Regime. Physical interpretation.

The program VisiMix LAMINAR is based on fundamental equations of shear stress, mass and energy equilibrium, and the classic solutions to some of these equations. These results are used in conjunction with experimental information on mixing, and experimental correlations on flow resistance on tank walls and agitator blades flown over with laminar and turbulent flow. The solution of these equations provides data on shear rates and shear stresses in critical areas of the tank volume (the zones near the agitator blades and near the tank wall) as a function of agitator geometry, rotational speed and properties of media. In addition, it provides information on the mixing intensity in different parts of the flow, as well as on the relative volumes of the zones of efficient mixing and the highest local shear stress.

At the next stage of calculations, this data is used for the approximate calculation of circulation flow in different points of the media. It serves as a basis for the development and application of stochastic models of mixing to obtain data on the frequencies of passages of different media fractions through the zones of efficient mixing and high shear stress. This important data allows you to understand, model, and scale-up mixing-dependent phenomena in laminar flow.

Calculations of the heat transfer from the laminar flow of agitated media are also based on calculated flow velocities. The mathematical models and the primary results of their application have been tested in the course of experimental research and verified by many years of industrial practice.

The main research data and mathematical models are described in the book Mixing in Liquid Media (by L. N. Braginsky, V. I. Begachev and V. M. Barabash, Chimia, Leningrad, Russia, 1984), and numerous publications in scientific journals.

VisiMix Laminar is the only program that calculates the physically meaningful parameters for analysis and scaling-up of processes dependent on blending and high shear treatment of Newtonian and non-Newtonian media.

The program is applicable in a wide range of flow conditions, including the range of relatively high Reynolds numbers on the border of a turbulent flow regime. Obviously, at the high Re numbers, the laminar character of the flow is distorted periodically by turbulent vortices. Due to such disturbances, a stepwise transition from laminar to turbulent mixing occurs. However, the exact course of the transition process is still unpredictable, and the VisiMix programs does not take into account these random macro- and micro-scale disturbances and are treating the flow as ‘totally’ laminar or ‘totally’ turbulent.

1. Definition of flow regime in mixing tanks.

Hydrodynamic flow regimes are determined based on the function FLOW RESISTANCE FACTOR vs. REYNOLDS NUMBER. It is understood that calculating resistance factors is based on the shear stress on the channel surface, or the local pressure drop on the obstacle (an object flowed over by the media, a turn or a narrow part of the channel, etc.). Calculation of the Reynolds number is based on the real or “equivalent” size of the channel or object, and on the real flow velocity. The following definitions are assumed:

A flow regime corresponding to an inverse proportion between the Resistance factor and the Reynolds number (Resistance factor = Constant / Reynolds number) is defined as a Laminar regime.

A flow regime corresponding to a weak dependence, or no dependence, of the Resistance factor on the Reynolds number (an exponential function with an exponent of - 0.25 – 0) is defined as a Turbulent regime.

A flow regime corresponding to the section of Resistance factor vs. Re number curve between the two extremes corresponding to Laminar and Turbulent regimes is defined as a Transitional regime.

It is clear that the Resistance factor vs. Re number function reflects the flow structure and the characteristics of the exchange of energy and mass in the flow.

In an agitated vessel, characteristics of flow structure and exchange are expressed by at least two different functions of the Resistance factor vs. Re number describing the flow resistance of the tank wall and of the impeller blades. In addition, VisiMix takes into account the additional flow resistance of baffles for baffled tanks (see NOTE).

One of these functions (Figure 1) describes the shear stress on the tank wall as a function of average flow velocity. Its general character is typical for all kinds of channels, but the exact coordinates of the curve depend on the relative sizes of the tank and impeller. The Reynolds flow number for this function is based on the channel size, or tank radius, and on the average tangential velocity in the tank.

According to results reported in the literature, the Resistance factor for Re numbers of 1500 and less is inversely proportional to the Re number. Therefore, the flow regime corresponding to these conditions is considered Laminar.

The section of the curve corresponding to the higher Reynolds numbers is sloped at about - 0.25, which corresponds to a Turbulent regime.

The second function (Figure 2) describes the flow resistance of the impeller blades flown over by the liquid media. The resistance factor of the blade is a function of the Re number for impeller blades expressed through the width of the blade and its relative velocity, i.e. the difference between the Tip velocity of impeller and the tangential velocity of the media. For low Re numbers (less than 1-5), the character of this function is strictly Laminar. At higher Re values, it becomes Transitional, and finally, Turbulent.

NOTE:

For baffled tanks, VisiMix 2K6 LAMINAR takes into account the additional flow resistance of baffles. However, the effect of baffles in a laminar regime usually is not significant.

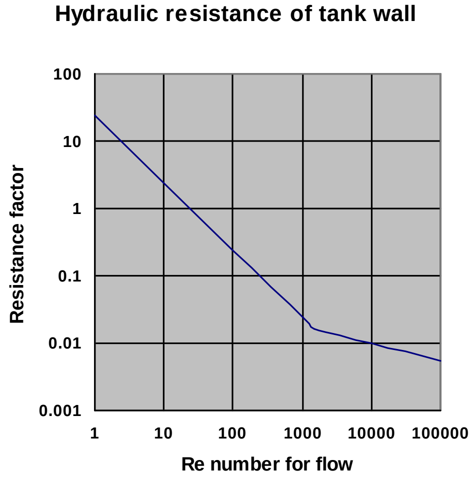

Figure 1.

It must be noted that Transitional or Turbulent flow conditions around the blades sometimes co-exist with strictly Laminar values of Reynolds number for flow. The existence of different flow conditions causes a change in the slope of the experimental function Power number vs. Re number.

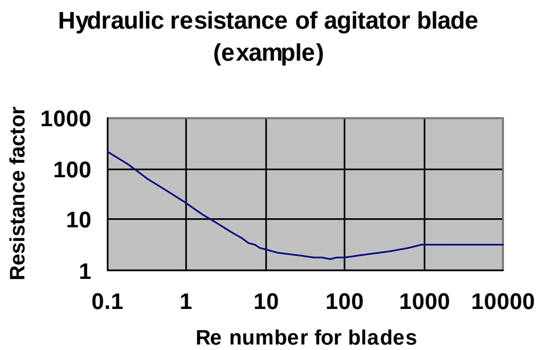

Figure 2.

In the range of Impeller Re numbers corresponding to the "minus one" slope of both functions, the Power number decreases in an inverse proportion to the Re number. In the range of higher Re numbers for the impeller blades, the slope decreases. In the range of a turbulent regime, for both resistance functions, only a weak dependence, if any, of the Power number on the Impeller Re number is observed. However, while the Re number for flow remains lower than 1500, the flow regime in the main part of a mixing tank is considered Laminar, even if a certain degree of turbulization may exist in the vicinity of the impeller blades.

On the other hand, it is obvious that at very high Re numbers, the laminar character of the flow is destroyed periodically by turbulent vortices. Due to such disturbances, a stepwise transition from laminar to turbulent mixing occurs, and the flow regime must be considered Transitional. The term Transitional regime of mixing, or Transitional flow regime is used here for flow Re numbers of 500 – 1500.

2. Interpretation of blending (macro-mixing) in laminar mixing regime.

From the point of view of mixing, the total volume of the tank may be considered as consisting of zones with two different types of flow conditions.

In one part of the volume, stable state tangential and axial laminar motion occurs, and stable layers of media moving with different velocities are formed. The laminar flow regime is characterized by the stable motion of such layers of liquid, with no significant exchange of substance between them. Mixing in such flows occurs as a result of the deformation caused by the different velocities in the neighboring layers. This mechanism contributes to the blending since it ensures the redistribution of substances along the flow directions, but it does not cause inter-mixing of the layers.

The stages of slow mixing due to deformation in tangential and axial flow alternate periodically with sharp changes in flow direction and structure followed by a fast random exchange of substance between the layers of media. This change of direction is a necessary condition for breaking the layers with different compositions, and consequently, for macro-scale homogenization of the media within the volume of the mixing zone.

The phenomena of fast exchange take place in certain parts of the flow, which we describe as zones of efficient mixing, or mixing zones. In tanks with Ribbon, Helical screw, or Anchor impellers, mixing zones are located around the turning points of the circulation flow close to the lower and upper edges of the impeller (Figure 3). In tanks with other impeller types, mixing zones are localized near the impeller blades (Figure 4). Passage of a portion of media through the mixing zone is described below as a mixing cycle.

Uniformity of a mixture is achieved when media from all points of the volume passes through the mixing zones. Due to non-uniform velocity distribution, the times needed for the liquid portions initially located in different points of the tank volume to reach the nearest mixing zone may differ by a few times, and the number of mixing cycles is thus a stochastic function of time.

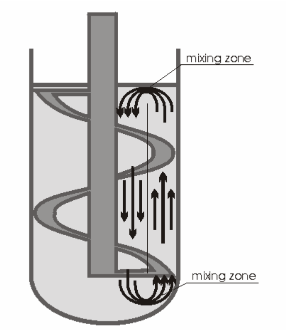

Figure 3.

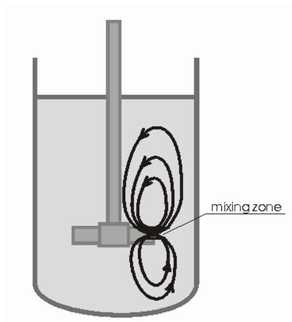

Figure 4.

The minimum number of mixing cycles required to achieve a certain predetermined technical result (a final degree of uniformity of viscous solution, distribution of temperature, selectivity of reaction, distribution of molecular mass in polymer production, etc.) depends on the process features and properties of the substances, for example, on the relation of densities and viscosities of components. However, for all processes, the degree of uniformity of a mixture in the tank is directly proportional to the average number of passages through the mixing zones, and inversely proportional to the part of the media that has passed through a mixing zone less than a given number of times.

3. High shear treatment of media (micro-scale mixing).

A characteristic scale of the random exchange of a substance in the mixing zone described in the previous paragraph is by order of magnitude close to the size of the impeller blades, and can provide macro-scale mixing. Repeated passages of the media through these zones result in a stepwise decrease of the scale of non-uniformity down to the microscopic level, and further distribution proceeds due to diffusion.

For a wide class of processes, more intensive treatment is necessary. For example, the manufacturing of multi-component and multiphase mixtures, such as paints, and cosmetics, requires a uniform distribution of various components, including powdered solids.

The solid material usually consists of very small (micron or sub-micron size) particles, which form big aggregates due to adhesive force. One of the main aims of mixing in such cases is the treatment of the media by extremely high shear stress. Such treatment helps to overcome adhesive forces, destroy aggregates, and achieve a high degree of uniformity on the microscopic level.

The most intensive treatment of the media takes place in high shear zones, which are formed in vicinity of the impeller blades due to big difference between velocities of the blade and the neighboring media (Figures 5, 6).

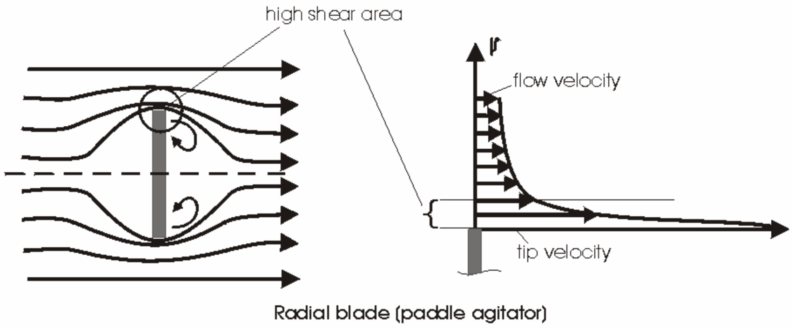

Figure 5.

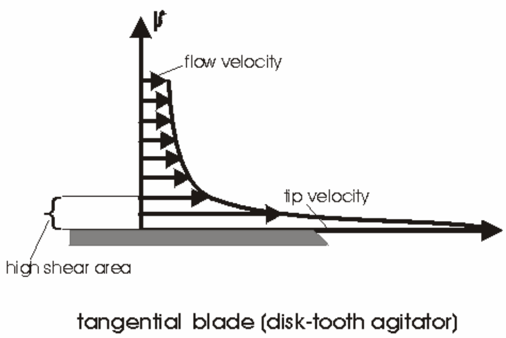

Figure 6.

The destruction of aggregates and extremely "thin" micro-mixing are achieved only in these high shear zones (referred to below as Impeller shear zones), and the final result depends on the following parameters:

Shear rate, or shear stress near the impeller. For each chemical composition of a mixture, there is a certain critical value of shear stress required for the efficient destruction of aggregates and the homogenization of the mixture. The shear rate and, consequently, the shear stress on the impeller blades increase in a direct proportion to the rotational velocity of the impeller. Therefore, operations that require high shear treatment are usually performed in tanks with high-speed impellers.

The degree of treatment of media in the high shear zone. This is best characterized by the relative quantity of the media subject to high shear treatment for less than a certain predetermined period. This part of the media may naturally contain large aggregates or non-uniform inclusions. In most practical cases, high shear zones constitute a small part of the tank volume. Therefore, the final "untreated" part of the media is a stochastic function of the total relative volume of the high shear zone near the impeller blades. This part increases with the number of mixing cycles that occur during the process time. In some cases, macro-scale mixing (blending) may be incomplete because not all the media has passed through a mixing zone even once. This occurs if the distribution of axial velocity in the tank is highly non-uniform (see Circulation flow rate, p.61), and it is taken into account in estimation of the untreated part of the media.

4. Formation of stagnant zones.

If the Yield stress for the media does not equal zero, Shear stress on the wall or in some areas inside the tank volume may be lower than Yield stress. As a result, stagnant zones form on the periphery of the tank, and mixing is limited to a zone around the impeller. In such cases, VisiMix LAMINAR performs calculation of torque and mixing power, and evaluation of volume of stagnant zone, but does not perform simulation of macro-scale flow. The program issues the message: "Formation of stagnant zones is expected. The configuration you have selected is not recommended...".