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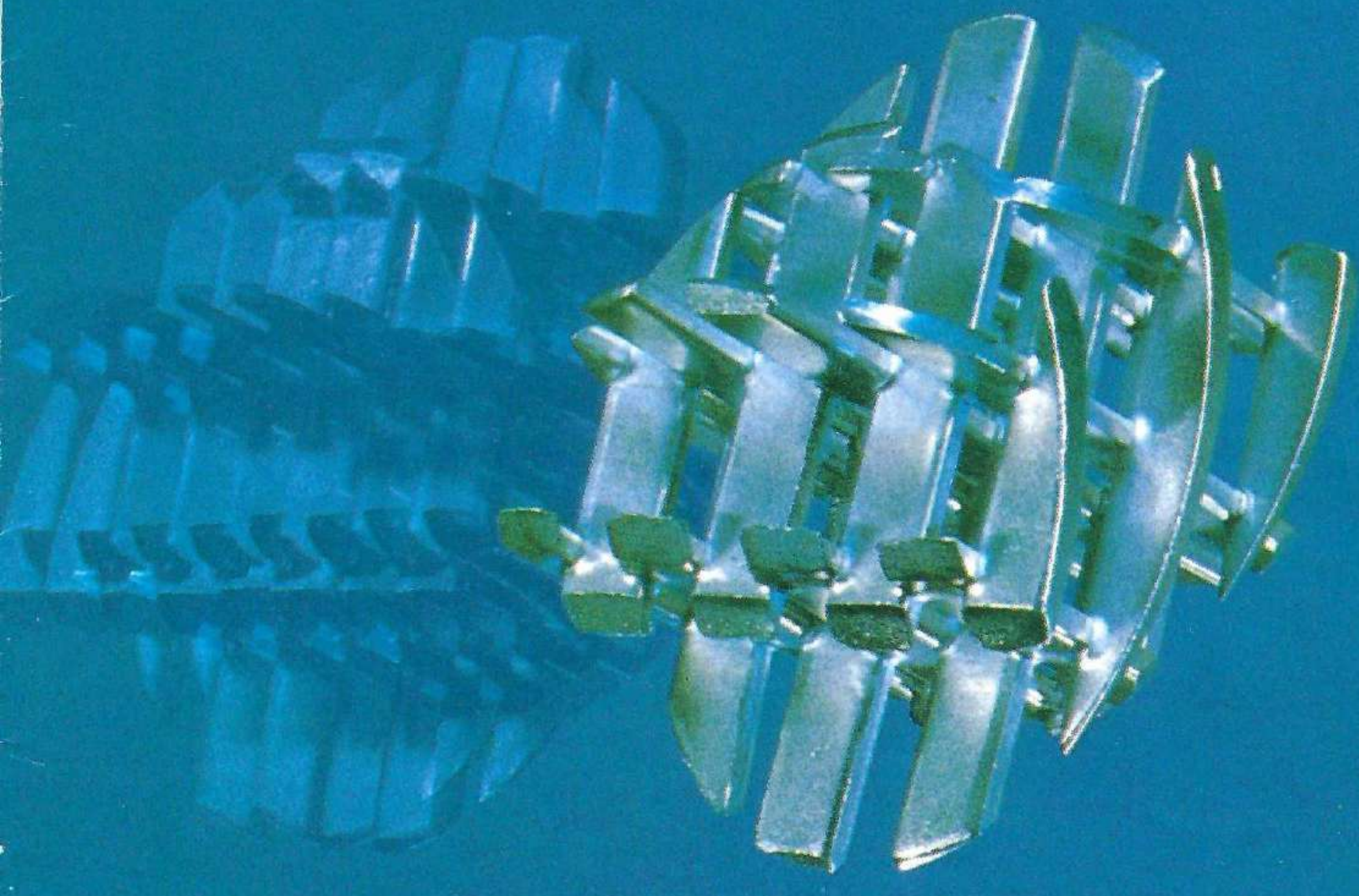

Mixing Efficiency of Static Mixing Units in Laminar Flow

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More than 30 different static mixing units are on the market worldwide. Most static mixer manufacturers claim that their product is the most efficient, but only a few can provide technical information on mixing efficiency and pressure drop. The only available information is often the number of layers created based on a simple layer formation law which, in fact, was never fully tested. (These exponential laws show that a mixing unit can produce over 10^6 divisions, but only 200 fluid layers can be verified optically, and even less by other methods.) Under these circumstances, it is difficult for the customer to select a suitable mixer since even the cheapest mixer is too expensive if it does not work properly.

This paper compares the mixing efficiency in laminar flow of the Koch/Sulzer static mixing unit with those of other manufacturers. Further, layer formation laws and manufacturer engineering data are compared with the actual mixing performance.

Test Procedures. The Swiss Federal Institute performed mixing experiments with most of the important static mixing devices; the apparatus used is shown in *Figure 1.* The test fluid was a glucose syrup with a viscosity of seven to nine Pa.s (7,000 to 9,000 cp). The homogeneity at the mixer outlet was measured with the conductivity tracer method where the tracer component (1) * had an electrical conductivity approximately seven times higher than the bulk fluid component (2). The flow ratio of tracer to bulk fluid was fed into the center of the pipe through a sparger (NPS 10 mm).

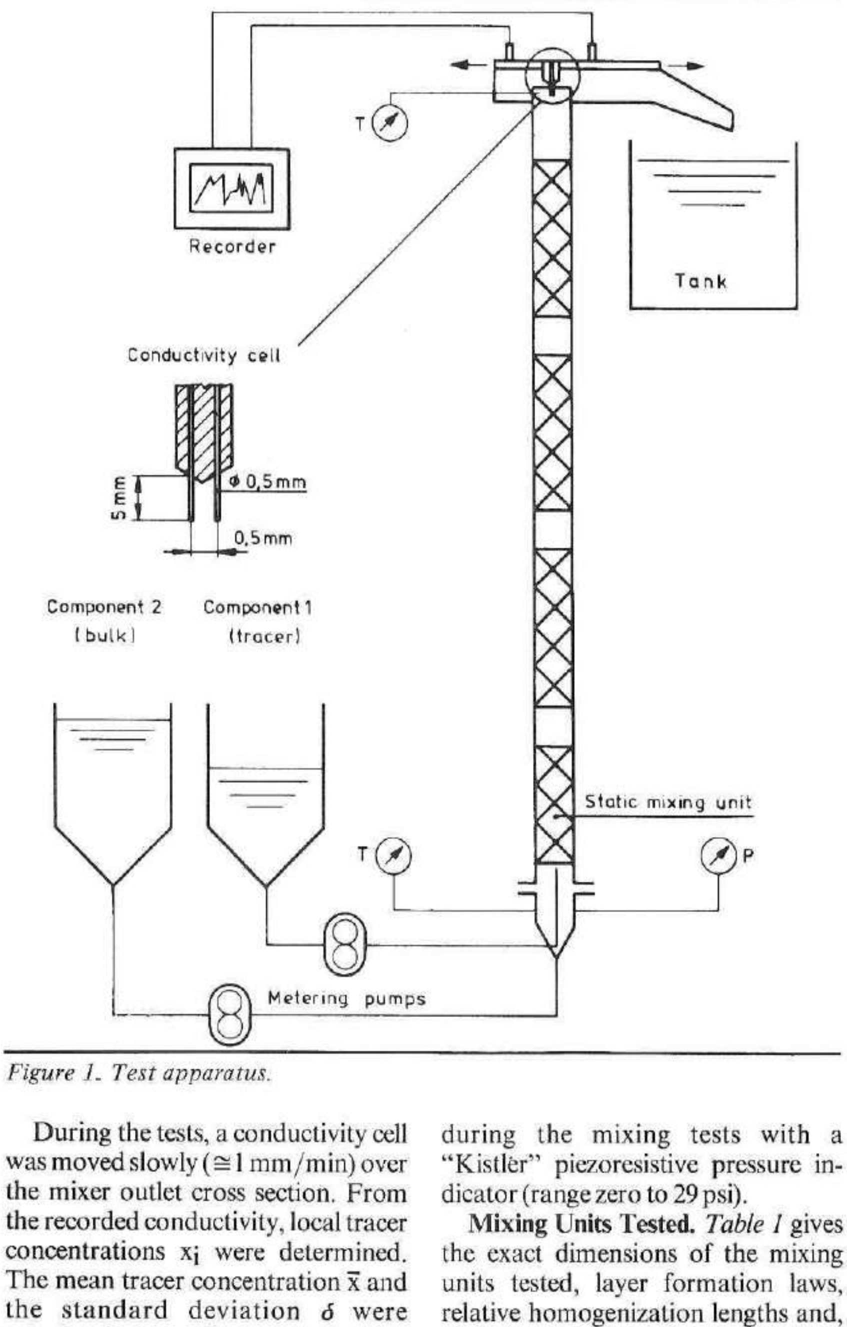

Figure 1. Test apparatus.

During the tests, a conductivity cell was moved slowly (≅1 mm/min) over the mixer outlet cross section. From the recorded conductivity, local tracer concentrations x_i were determined. The mean tracer concentration $\bar{x}$ and the standard deviation σ were calculated according to standard mathematical techniques as follows:

$$\bar{x} = \frac{\sum_{i=1}^{n} x_i}{n} \qquad \sigma = \sqrt{\frac{\sum_{i=1}^{n} (x_i - \bar{x})^2}{n-1}} \qquad \text{(a)}$$

The pressure drop was measured during the mixing tests with a "Kistler" piezoresistive pressure indicator (range zero to 29 psi).

Mixing Units Tested. *Table 1* gives the exact dimensions of the mixing units tested, layer formation laws, relative homogenization lengths and, where available, other information about homogeneity, such as $\sigma/\bar{x}$ and pressure drop information expressed as $NeRe_D$ numbers (*See equation C*).

The degree to which homogeneity is achieved is often expressed in terms of the number of layers or stream divisions formed. Some sort of an ex-

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*Numbers in parentheses refer to references at end of article.

Table 1. Mixing Units Tested

Mixing Units		Dimensions[4]						Specified design data according to manufacturers sales brochures			
Name	Type	D (mm)	L_E (mm)	E (–)	L/D	tested (–)		N (–)	L/D_h (–)	Homogeneity N or $\delta/\bar{x}$ (–)	$NeRe_D$ (–)
SMX	16	50	50	0.91	5	7	11	–	9	$\delta/x = 0.05$	1200
SMXL	26	50	180	0.96	–	19	30	–	26	$\delta/x = 0.05$	250
SMV	12[3)]	50	50	0.88	–	7	14	–			
Kenics	–	50	80	0.85	9.6	19.2	28.4	2.2^n	29 (38)	$5.2\ 10^5$	184
Etoflo	HV	40	62	0.92	–	18.3	37	–	40	–	–
Komax	–	50	50	0.86	–	–	25	2.2^n	21 (32)	$2.1\ 10^6$	592
Lightnin	Standard	50	77	0.86	9.2	18.4	28	3.2^{-1}	–	–	236
PMR	D-5	40	40	0.83	10	20	–	3^n	–	–	–
Cunningham	–	20	100	0.5	5	–	–	4^n	5[1)]	1024	–
Toray	Hi-Mixer	40/54	41	0.46	–	6	10	2.4^n	–	–	1067
N-Form	–	15	22	0.85	–	–	34	–	22	–	480
Ross	ISG	40	40	0.35	10	14	24	2.4^n	10 (14)	$2.1\ 10^6$	7300

1) used as mixing head for injection molding machines. 3) type recommended for turbulent flow. 4) for symbols used, see Nomenclature.

Mixing unit	Measured values		Comparisons				
	L/D for $\sigma/\bar{x}=0.05$	$NeRe_D$	Volume*	Holdup*	Diameter*	Length*	Pressure drop**
SMX	9	1237	1	1	1	1	1
SMXL	26	245	1.8	1.8	0.84	2.4	0.6
SMV	18	1430	4.6	4.5	1.3	2.7	2.3
Kenics	29	220	1.9	1.8	0.84	2.7	0.6
Etoflo HV	32	190	2	2	0.84	2.7	0.6
Komax	38	620	8.9	8.2	1.3	5.4	2.1
Lightnin	100	290	29	27	1.4	15.3	2.6
PMR	320	500	511	460	2.4	86	14.5
Cunningham	←		No mixing				→
Toray	13	1150	1.94	0.88	1.1	1.6	1.35
N-Form	29[1)]	544[3)]	4.5	3.8	1.1	3.6	1.40
Ross ISG	10[2)]	9600	9.6	3.4	2.1	2.3	8.6

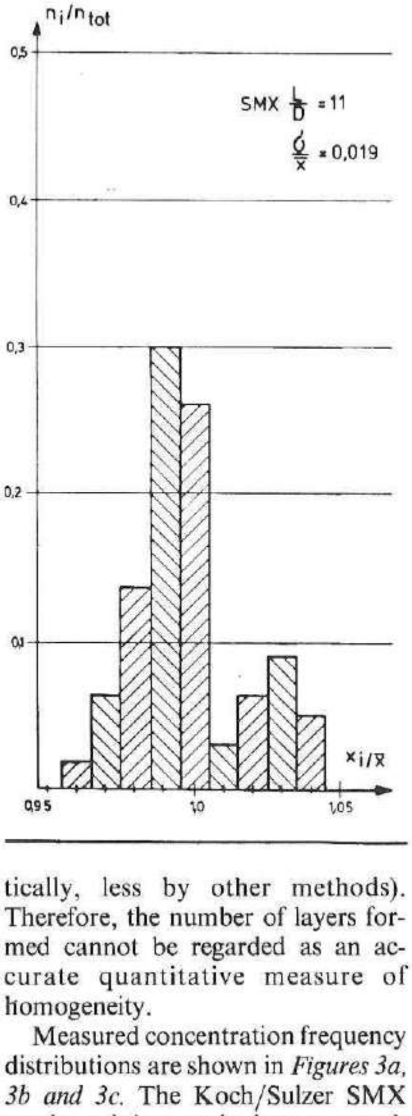
1) according to [2], 2) according to [3], 3) according to [4]

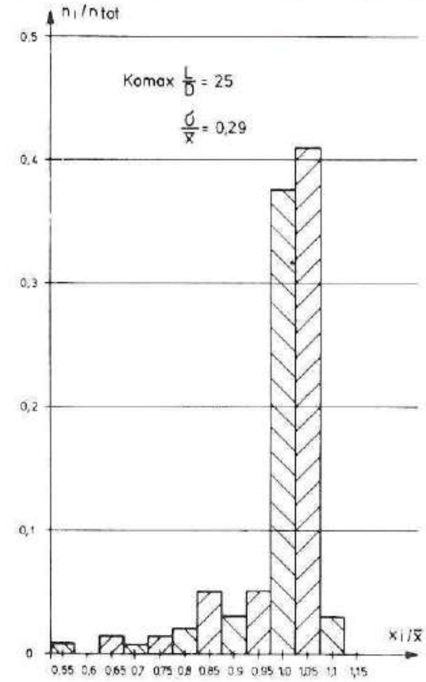
* Multiple of volume, holdup diameter and length as compared to SMX for equal η, $\dot{V}$, Δp and $\sigma/\bar{x}$

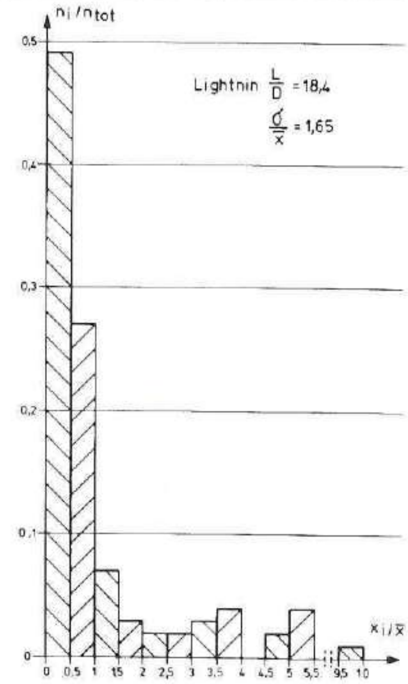
** Multiple of Δp as compared to SMX for equal η, $\dot{V}$, D and $\sigma/\bar{x}$

Table 2. Comparison of static mixers.

ponential layer formation law is used to calculate the number of layers formed as a function of the number of cutting edges. These laws, however, do not accurately describe homogeneity at the mixing unit's exit – they make no allowance for the influence of the volume ratios of the streams being mixed, and they claim that all layers are of uniform thickness, which is not true. Also, the layer formation laws cannot be verified experimentally (they predict the formation of over 10^6 layers but only 200 layers can be verified op-







Figures 3a, 3b, 3c—Measured concentration frequency distributions.

tically, less by other methods). Therefore, the number of layers formed cannot be regarded as an accurate quantitative measure of homogeneity.

Measured concentration frequency distributions are shown in *Figures 3a, 3b and 3c.* The Koch/Sulzer SMX static mixing unit has a much narrower concentration distribution (0.95 to 1.05) than either the Komax or the Lightnin mixer. Not shown is the distribution for the PMR mixer since practically no mixing takes place (the distribution for the PMR is the same as the inlet for 90 percent samples with $x_i/\bar{x}=0$ and 10 percent samples with $x_i/\bar{x}=10$ for $x=0.1$).

The desired degree of homogeneity for most industrial mixing applications is reached when the variation coefficient ($\delta/\bar{x}$) is 0.05 or less. A comparison of mixing units tested is shown as follows:

Mixing Unit	$\delta/\bar{x}$	L/D
SMX	0.019	11.0
Komax	0.290	25.0
Lightnin	1.650	18.4

Homogenization Lengths. In *Figure 4*, the measured homogeneity is represented as a variation coefficient $\delta/\bar{x}$ versus relative mixing unit length L/D. The variation coefficient at the mixer inlet was calculated according to:

$$\frac{\sigma_o}{\bar{x}} = \frac{\sqrt{\bar{x}\,(1-\bar{x})}}{\bar{x}} = \frac{1}{\bar{x}} - 1 \qquad \text{(b)}$$

Accepting a variation coefficient of $\delta/\bar{x} = 0.05$ as homogeneous results in the homogenization lengths presented in *Table 2.* The SMX mixer has the shortest possible mixer length. The "low pressure drop" mixers require a relatively long homogenization length. The Koch/Sulzer type SMV, which is normally recommended for turbulent flow, is not as efficient as the type SMX. Some mixers need such extensive relative homogenization lengths that they are not efficient at all in laminar flow. The Toray and the Ross ISG mixers approach a relative homogenization length comparable to the SMX.

A comparison with the layer formation laws given in *Table 1* shows that some of the mixers have inefficient layer formation rates. The layer thickness predicted by the layer formation law for the actual measured homogenzation length for the Kenics mixer (L/D = 27, 18 elements) would be:

$$\delta = \frac{D}{N} = \frac{50\text{ mm}}{2.2^{18}} \cong 10^{-4}\text{mm}$$

The predicted layer thickness for Lightnin mixer (L/D = 100, 65 elements) would be:

$$\delta = \frac{50\text{ mm}}{3.2^{65-1}} \cong 10^{-18}\text{ mm}$$

Note that the size of a molecule is on the order of 10^{-6} mm. This also shows clearly that layer formation laws do not accurately describe the mixing result at the mixing unit's exit. (They might be used to demonstrate the mixing effect near the mixer inlet, but only if they are verified by mixing tests.)

This comparison, however, does not give a complete picture of the efficiency. For a correct comparison the pressure drop required for a homogeneous mix must be included.

Pressure Drop. The pressure drop (Δp_l) in a static mixing unit with laminar flow is:

$$\Delta p_l = \frac{4}{\pi}\; NeRe_D\; \frac{\eta\,\dot{V}}{D^3}\,\frac{L}{D} \qquad \text{(c)}$$

where $NeRe_D$ is a constant depending only on the element geometry. For each test the flow rate and the viscosity was measured to

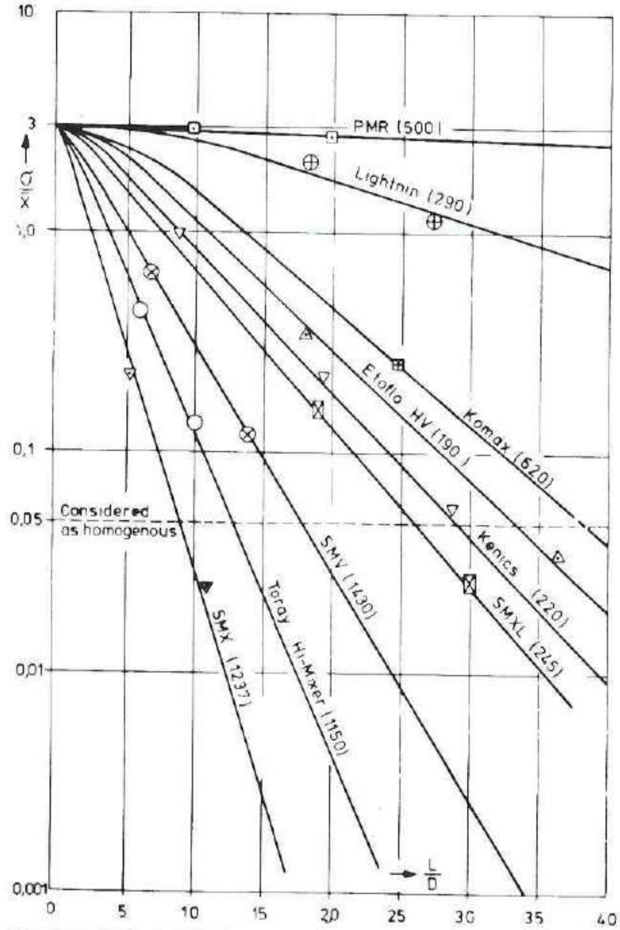


Figure 4. Variation coefficient as a function of relative mixer length. Values in ( ) measured $NeRe_D$. Note that the SMV is the one recommended for turbulent flow.

Nomenclature

Symbols Used

D	(m)	Mixing unit inside diameter
H	(m^3)	Liquid holdup
L	(m)	Mixer length
L_E	(m)	Mixing element length
N	(–)	Number of layers
Ne	(–)	Newton number
n, n_i	(–)	Number of elements or number of samples, number of samples in class i
P_1	(Pa)	Pressure drop with laminar flow (1 bar = 10^5 Pa)
Re_D	(–)	Reynolds number reffered to empty pipe
V	(m^3)	Mixer volume
$\dot V$	(m^3/s)	Volume flow rate
W	(-)	Specific power requirement
W_{1V}	(-)	Specific power requirement in laminar flow with respect to volume
W_{1D}	(-)	Specific power requirement in laminar flow with respect to diameter
W_{1L}	(-)	Specific power requirement in laminar flow with respect to length
x_i	(-)	Measured local tracer concentration
$\bar{x}$	(-)	Mean tracer concentration
δ	(m)	Layer thickness
ϵ	(-)	Void fraction
η	(Pas)	Dynamic viscosity
δ	(-)	Standard deviation from the mean concentration

Indices

h homogeneous
l laminar
o at mixer inlet
D with respect to diameter
L with respect to length
V with respect to volume

determine Δp_1. The viscosity was measured with a Contraves Rheomat 30 viscosimeter. Note that glucose syrup is a Newtonian fluid. For non-Newtonian fluids, η must be replaced by the representative viscosity η_{rep}, which is a function of the shear rate.

The resulting $NeRe_D$ numbers are included in *Table 2*. A comparison with the values calculated from the sales brochures (*Table 1*) shows that the measured pressure drop is always somewhat higher than the specified value.

Final Comparison Including Pressure Drop and Mixing Characteristics. A mixing task for a static mixing unit is completely specified by the product properties at operating conditions, flow rate, feed stream ratios, pressure drop, the required homogeneity, and often by a required pipe diameter as well.

We can now compare mixing units which can compete with the given specification with respect to their volume (or liquid holdup), diameter, and length or the pressure drop if the diameter is specified.

Specific power requirement groups W_{IV}, W_{ID}, W_{IL}, as they were used by Streiff (5) allow such comparisons in a dimensionless form. These comparisons are given in *Table 2* relative to the SMX mixer for a homogeneity of $\delta/\bar{x} = 0.05$ with $\bar{x} = 0.1$. Thereby, the following relations hold true:

Here (L/D) is the measured relative homogenization length of the mixer in question that is required to produce an acceptable mix.

If the pressure drop in a given pipe diameter has to be minimized, regardless of the mixer length, the Koch/Sulzer SMXL mixer is at least as efficient as the best "low pressure drop" mixers such as Kenics or Etoflo.

Mixing unit volume (liquid holdup $H = \epsilon V$)
$$V = W_{lV} \frac{\dot V \eta}{\Delta p} = NeRe_D \; (L/D)^2 \; \frac{\dot V \eta}{\Delta p} \qquad \text{(d)}$$

Mixing unit diameter
$$D^3 = \frac{4}{\pi} W_{lD} \frac{\dot V \eta}{\Delta p} = \frac{4}{\pi} NeRe_D (L/D) \frac{\dot V \eta}{\Delta p} \qquad \text{(e)}$$

Mixing unit length
$$L^3 = \frac{4}{\pi} W_{lL} \frac{\dot V \eta}{\Delta p} = \frac{4}{\pi} NeRe_D (L/D)^4 \frac{\dot V \eta}{\Delta p} \qquad \text{(f)}$$

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