Static Mixing Technology

By Dr. Virendra V. Chavan*

Introduction

IN recent years, several trade names have appeared in static mixing area. Kenics, Sulzer, Koch, Prematechnik, Komax, and Hi-mixer are amongst the fifty-odd different types of mixers that are marketed in the Western world. Most of these were developed in the last 15-20 years. Static Mixing Technology is, however, many years old. Earliest mention of it was in an American Patent issued in 1930, where a twisted helical type was used to improve the heat transfer. Since then, static mixers are used for several different types of operations involving gases, liquids or solids and often more than one phase. Operations such as aeration, blending, mixing, heat or mass transfer are successfully improved with static mixers inserts. This article explains the principle of working of these mixers. Also some of the published data that are available on the static mixers common in the West, are also analysed to elaborate these concepts.

Principles Of Static Mixing

Static mixing is achieved by putting a series of well-designed obstructions in a flowing stream in such a way that the stream is periodically divided; the parts obtained thereby are displaced through a certain angle, usually 90°. The stream will thus be divided into a number of small parts which are mingled with each other. Fig. 1 describes how the mixer is placed in a pipe.

At extremely low Reynolds numbers (say $\leqslant 1$ in a pipe), when the effects of secondary motion or whirls created by the mixing elements are absent, static mixing may be considered to be purely distributive. It means that the flow division and displacement through a certain angle are the only operating mechanisms. A simple rule may then be derived to predict the number of layers at the exit of a tube; it being:

$$N = c\,(s+1)^n \qquad (1)$$

Where N is the number of layers at the exit, 'c' is the number of components (or layers) at the start, 's' is the number of cutting actions per element and 'n' is the number of elements. For example, helical designs have 's' equal to 1 and when one liquid stream is flowing in a tube with 'n' such elements, we have

$$N = 2^n \qquad (2)$$

Often, equation (1) will assume a complicated form when elements themselves have a complex geometry.

At higher Reynolds number, the contribution of radial flows towards the improvement of mixing becomes substantial. In such cases, even for simple geometries, the above equation will not hold. Further, the above rule does not take account of several relevant physical phenomena, such as flow-ratio or viscosity ratios of blending liquids. Any useful mathematical analysis taking all such factors into consideration will be difficult and have not been tried in the context of static mixers. However, enough experimental data are available to show the improved performance with the use of static mixers even in the turbulence regime of flow.

Hydrodynamics And RTD

As in the most complex continuous systems, the liquid-flow and the motion of solid particles in a static mixer are best analysed and understood by doing residence time distribution (RTD) measurements. Fig. 2 gives typical curves for $F(\phi)$ function which defines the volumetric part of the stream which had residence time in the apparatus of less than ϕ; ϕ being the dimensionless residence time, t/t. It is seen that RTD of static mixers closely approximates the plug-flow, which is a definite improvement over pipe-flow and stirred vessels. This is most desired situation, especially in the designs of continuous reactors. In solid particles flow, it appears that the presence of static mixer can break agglomerates and thus evens out size distribution effects to obtain RTD close to the plug flow.

Pressure Drops

Friction factor f, defined as:

$$f = \frac{\Delta_p\, D}{\frac{1}{2}\,\rho\, v^2\, L} \qquad (3)$$

the symbols having the usual meaning given in the Nomenclature, were

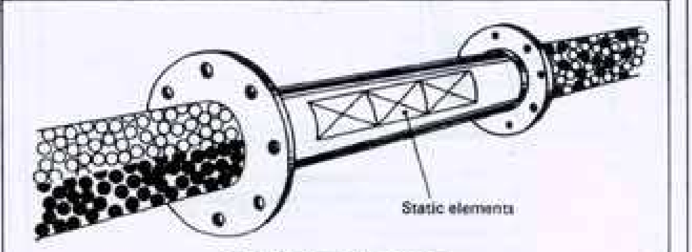

Fig. 1. Static mixing concept.

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found to be strongly dependant on the geometry of the mixer. Fig. 3 demonstrates this effect quantitatively. In order to evaluate the relative efficiency of different designs such data could be useful. Wilkinson and Cliff have correlated the pressure drop data with equation similar to that of packed bed, which is:

$$f = \frac{460}{Re} + 2 \quad \ldots\ldots\ldots\ldots\ldots\ldots \quad (4)$$

It is valid up to Re of 100. According to the same authors, the equation may also be used for viscous non-Newtonian liquids as long as a generalised Reynolds number is substituted. Generalised Reynolds number is defined as

$$Re_{generalised} = \frac{8\,\rho\,D^n\,V^{2-n}}{k\,\left(\frac{6n+2}{n}\right)^n} \quad \ldots\ldots \quad (5)$$

'k' and 'n' being power law constants obtained from shear stress vs shear rate data on a viscometer in a proper range of shear rates and at appropriate temperature. It appeared that viscoelasticity, exhibited by 1% polyacrylamide solution, did not influence the pressure drop in any way. This conclusion, however, should not be taken as applicable for all the designs of static mixers. The adverse effects of fluid elasticity in converging flows on porous media are well known. Such effects can also be expected here if the velocity gradients in the directions of flow are large compared to the inverse of the fluid relaxation time.

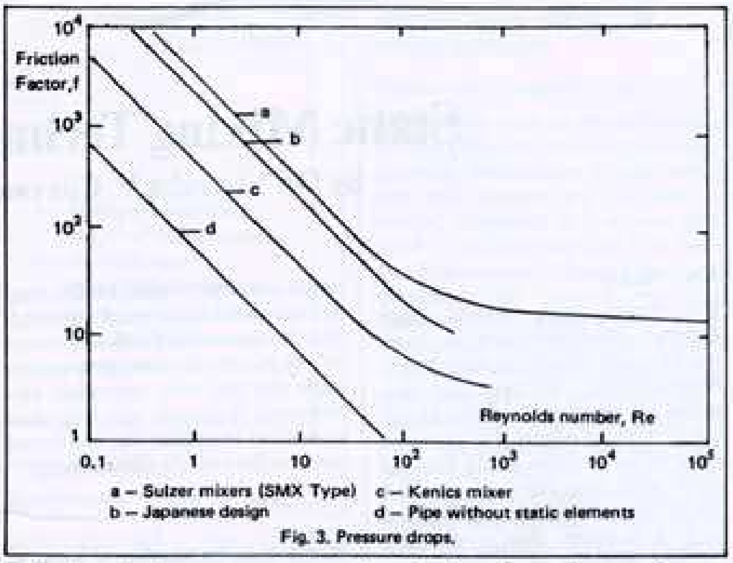


Fig. 3. Pressure drops.

Pressure drops appear to increase substantially because of the presence of static elements. However, considering that a given job is done more efficiently and short length of pipe is often required, the energy costs in the final analysis do not appear to be very high.

Mixing And Blending

In order to assess the performance of static mixers properly, the criteria and concepts used to quantify the quality of mixtures should be well understood. The requirements of scale of scrutiny and segregation are determined by the purpose of mixing, whereas one fixes the values for intensity of segregation depending upon the quality one desires. Generally,

$$(\sigma^2/\sigma_0^2) \approx 10^{-4} \text{ or } (\sigma/\bar{c}) \simeq 5\times10^{-2}$$

appear to be accepted values.

Data on intensity of segregation and degree of mixedness are summarised in Fig. 4, 5 and 6. Hartung and Hiby used the famous method of Danckwerts to measure the intensity of segregation; the scale of scrutiny being closer to the molecular size. Their results are shown in Fig. 4. It is obvious from these data that the presence of static mixers brings about several times reduction in the intensity of segregation and causes consequently an improvement in the degree of mixing. It is noteworthy that even the simple shishkebab type of arrangement also helps to improve mixing. However, one should choose judiciously, taking pressure drop also into account.

Pahl and Muschelknantz have done systematic work on the mixing of static elements in laminar flow. They have used the electrical conductivity method and have measured the radial distribution of the conductivity at a given length. Their plots of intensity of segregation vs the length to diameter ratio are reproduced in Fig. 5. In the absence of static mixers and thus without the advantages of the distributive mixing, the mixing in a pipe will be

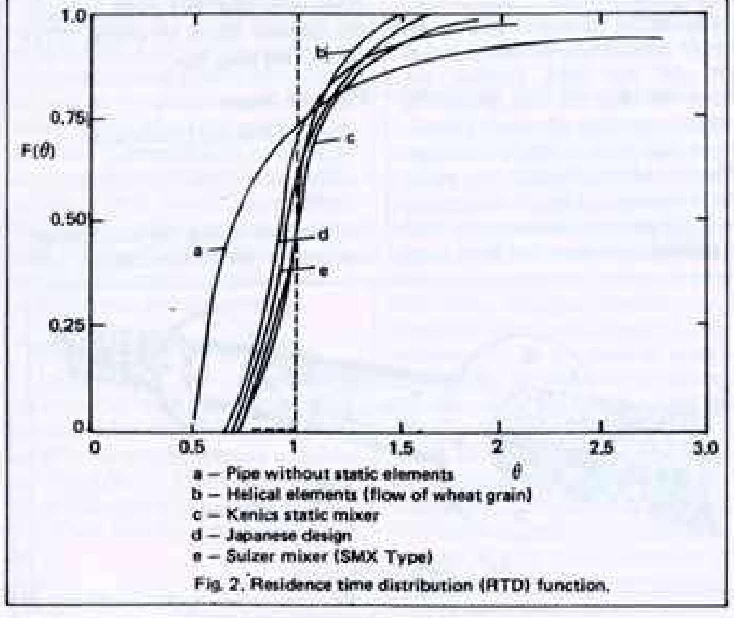
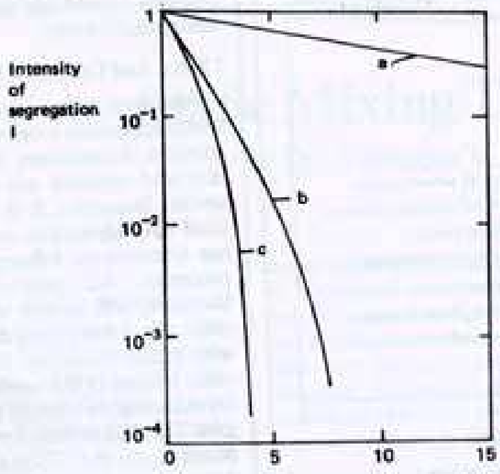


Fig. 2. Residence time distribution (RTD) function.



(Note: $I = \sigma^2/\sigma_0^2$; Re = 8000)

a — Pipe without static elements b — Kenics mixer c — Shishkebab arrangement

Fig. 4. Intensity of segregation at high Reynolds number.

caused by shearing (the so-called laminar shear mixing) or by convective diffusion. For high viscosity liquids, molecular diffusion will have extremely low values and convective diffusion will not cause a great deal of mixing unless Reynolds numbers are sufficiently large. Further, since laminar shear mixing is also ineffective, in pipeflow, at the small length to diameter ratios, one does not expect any mixing to occur. The plots in Fig. 5 show the usefulness of the static elements. Mixing of solid particles with static elements has been studied by Chen et al and Lai and Fan. Their data are replotted in Fig. 6. Improvements in mixing is clearly achieved by the static elements, even for gases.

Heat And Mass Transfer

Heat transfer through the wall of a pipe or tube is common in chemical and allied technology. Often, improvements are sought after. Several ideas, such as the use of internal fins or the addition of polymer to the liquids in turbulent flow, have been tried and are being used. Static mixers also offer this possibility of an improved heat transfer. Together with the enhancement in the heat transfer, one also has an extra advantage of mixing, because of which one obtains flat radial temperature profile. One thus has an extremely useful system.

Laminar flow heat transfer in a pipe is described by two equations

For $Re.\,Pr.\,\frac{D}{L} > 20$ (i.e. $\frac{L}{D} < \frac{Re.\,Pr.}{20}$)

one has $Nu = 1.62\,(Re.\,Pr.\,\frac{D}{L})^{\frac{1}{3}}$ . . . . . (6)

and for $Re.\,Pr.\,\frac{D}{L} <$ 10 (i.e. $\frac{L}{D} > \frac{Re.\,Pr.}{10}$)

One has

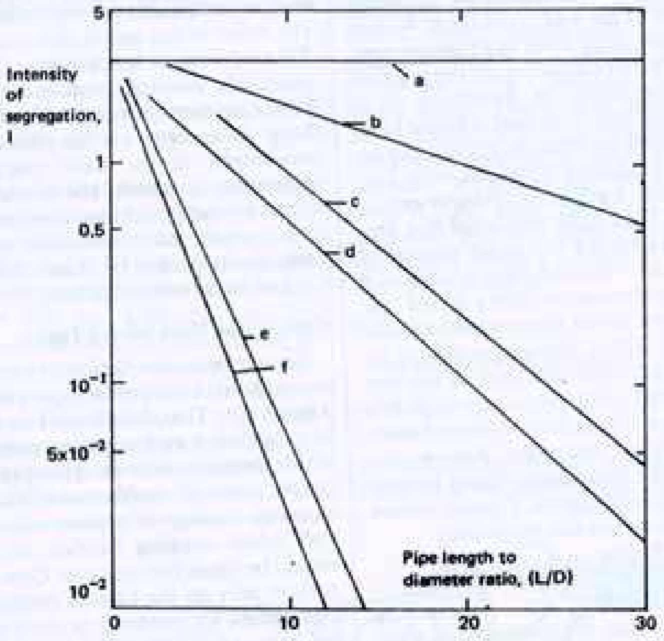
$Nu = 3.66$ . . . . (7)

for calculation. Correction to these are brought about by Sieder and Tate and an experimentally verified equation:

$Nu = 1.86\,(Re.\,Pr.\,\frac{D}{L})^{\frac{1}{3}}\,(\frac{\eta}{\eta_w})^{\frac{1}{7}}$ . . . . . . (8)

is proposed. These equations should be compared with those given for commercial static mixers. A clear advantage in enhancement of heat transfer by a factor 2 to 3 appears to be achieved by the static mixer inserts. Such improvement is comparable with the interval fins or an ordinary twisted tape inserts. However, with the mixing-elements one also achieves better temperature equalisation.

For turbulent flow, a three-fold increase over the heat transfer coefficients in pipes (as given by Dittus



(Note: $I = \sigma/\bar{c}$, coefficient of variance;
$\bar{c} = 0.1, Re \leqslant 1$)

a — Pipe without static elements
b — In-line blender of lightning
c — Komax mixer
d — Kenics mixer
e — Japanese design
f — Sulzer mixer (SMX Type)

Fig. 5. Intensity of segregation at low Reynolds numbers.

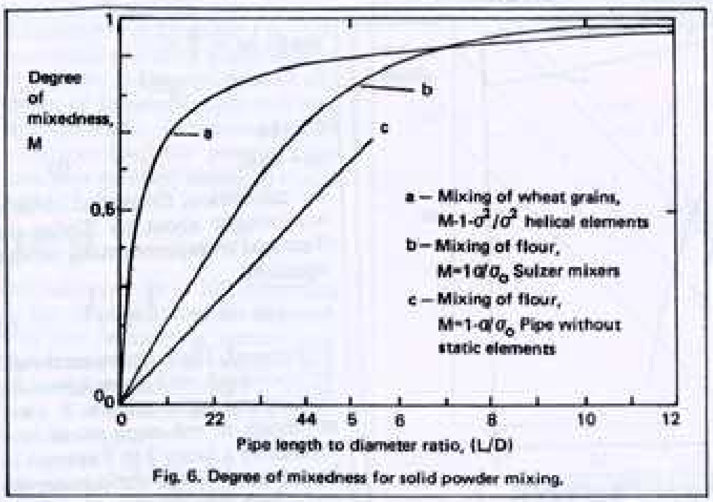


Fig. 6. Degree of mixedness for solid powder mixing.

and Boelter equation) have been reported in the literature. Data on intermittent use of static elements followed by an empty pipe are given by van der Meer and Hoogendoorn.

Published investigations on mass transfer in static mixers is rather limited. Morris and Proctor have measured the coefficient of mass transfer from wall to the turbulent flow of gas and found them 4 times greater than those in an empty pipe. Extremely revealing are the practical investigations of Merchunk et al where they have used different types of static elements to recover copper from aqueous solutions with Lix-type of reactant in a tubular extractor. They have concluded that they could extract the equal amount of copper from a tubular extractor with static elements as from a stirred tank as long as the power input was the same. Extra advantages offered by the static elements such as low cost and ease of operation help to make a choice in their favour. Some patents on liquid extraction process also note the use of static mixers for process improvements. Russian interest in this item is also noteworthy.

Emulsification And Coagulation

Middleman has conclusively shown that the presence of static mixers substantially improves the drop break-up phenomena in turbulent flow ($Re \geqslant 3500$). Sauter mean drop diameter is reduced by a factor 7.3. Data may be simply correlated by

$$\frac{d_{32}}{D} = K\, We^{-0.6}\, Re^{0.1} \quad \ldots\ldots\ldots \quad (9)$$

in the range $10^3 < We < 10^5$. The constant 'K' obviously takes much higher values (0.07 to 0.30) when the pipes are fitted with static mixing elements. It should be noted that the data of Middleman, which are in the range $10 < We < 10^3$, cannot be described by the above equation. One will then need more in-depth study to understand the mechanism. The writer of this article in a review discusses various mechanisms that control the emulsification and also the coagulation process which may throw some light on the physical phenomena in the static mixing equipment. Successful use of static mixers for the coagulation operation in the waste water treatment has been demonstrated by Aisin Seiki Co. Ltd. in their recent patent.

Comparison With Stirred Tanks

For a proper comparison, the criterion should be the money spent for a given job. Therefore, factors such as capital cost and operating costs, which should include energy expenditure, costs of maintenance and cleaning, wastage of process materials when charging batches, etc., should be taken into account. Comparison only on the basis of energy expenditure for pumping or driving has been done by Streiff, where he notes the superiority of static mixers. When all the other factors are taken into account, how the static mixers compare with the stirred tanks will very much depend on the particular process. But in most processes of chemicals, food or polymer industries, one can expect static mixers, if properly chosen and designed, to do substantially better.

Choice And Design Of Static Mixer

Processes such as emulsification, deemulsification (coalescence), coagulation, flocculation, deagglomeration and aeration are common to several industries. It is known that local hydrodynamics and flow field has tremendous influence on such processes. No process engineer, therefore, will accept that a given static mixer design can do all the job with equal efficiency. None of the static mixers in the worldwide market are versatile enough to do all the jobs. The choice then very much depends upon the process for which the mixing unit is being bought. The concept of a special design for a given job has only recently entered in the static mixing. We should indeed be very selective. Remember, no one type of elements can efficiently do all the jobs. ■

Nomenclature

c	number of components
c_i	concentration of i^{th} sample
$\bar{c}$	average concentration
d_{32}	sauter mean (drop) diameter
d_h	hydraulic diameter
f	friction factor $\frac{\Delta p}{\frac{1}{2}\rho v^2}\frac{D}{L}$
$F(\theta)$	F-function representing RTD
I	intensity of segregation
k	consistency index
L	pipe length
M	degree of mixedness
n	number of static elements (also flow index in equation (5) or number of samples in statistical equations in the Apendix)
N	number of layers
Nu	Nusselt number $(\alpha D/\lambda)$
Δp	pressure drop
Q	volume flow rate
r_s	striation thickness
$Re.$	Reynolds number $\frac{D v \rho}{\eta}$
s	number of cutting actions per element
S	scale of segregation
t	residence time
v	average velocity $(4Q/\pi D^2)$
We	Weber number $(D v^2 \rho/\sigma)$
$\bar{t}$	average residence time

Greek Symbols

α	heat transfer coefficient
η	viscosity
η_w	viscosity at wall
θ	dimensionless residence time
λ	conductivity
ρ	density
σ	standard deviation (also surface tension in Weber number, We)
σ_0	standard deviation at start
σ^2	variance
σ_0^2	variance at start