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Up to 50% smaller pressure drop
Up to 40% shorter residence time

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Static mixer for laminar flow

Fluitec CSE-X® mixer

The Fluitec CSE-X® mixer is designed for applications that have to meet very exacting requirements. This document describes the new CSE-X/6-12 mixer and its outstanding properties. It extends Fluitec's static mixer family, strengthening the company's position as global market leader. The mixer's exceptional performance, which is achieved by opening the wall area and partially waisting the bars, is explained in the following with the aid of examples. This Fluitec mixer combines a low resistance factor with optimal mixing efficiency, providing access to a wide range of applications. From gasification through emulsification and homogenisation to mixing processes involving extreme viscosity ratios, Fluitec CSE-X® mixers have become the system of choice over the years. The new mixer model reduces the pressure drop by up to 50% without compromising mixing performance.

Principles of static mixing

Static mixers are apparatus with fixed, geometrically shaped elements that mix the product flowing through them with the help of kinetic energy only. Since maintenance and wear are negligible, only a comparatively small space is required for installation and the equipment is suitable for a wide viscosity range, static mixers are today an increasingly popular alternative for continuous and batch processes.

The mixing processes which take place in Fluitec mixers are not random but reproducible and optimised. The high productivity and low energy consumption have a positive impact on both the capital investment and operating costs. Industrial scale plant can moreover be reliably sized on the basis of longstanding experience and the results of pilot tests. The scale-up risk is therefore minimised.

The innovative machine presented here is the only one of its kind in the static mixing market. It is compared in this document with other conventional and well-established X mixer models, which it will in future replace.

The new Fluitec mixer is used exclusively in the laminar flow regime. The flow regime is determined by the Reynolds number and the properties of the fluids to be mixed.

$$Re = \frac{\rho \cdot w \cdot D}{\eta} = \frac{\rho \cdot w \cdot d_h}{\varepsilon \cdot \eta} \qquad \text{Equation 1}$$

In turbulent flow (Re > 2400) the fluid particles move randomly in all directions.

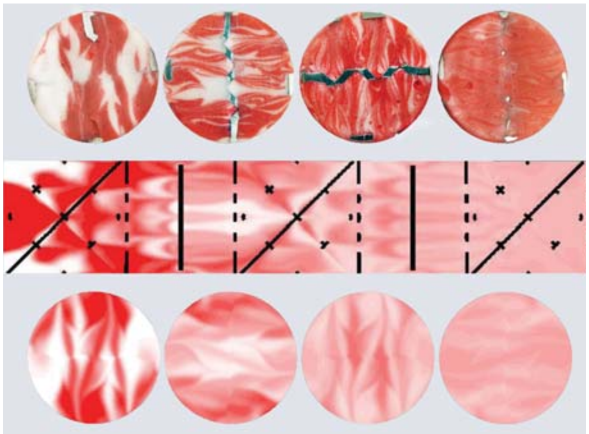

Fig. 1 Epoxy section and CFD calculation for the CSE-X/6-12 mixer

In laminar flow (Re < 20) the fluid particles move in layers along straight, parallel paths. The Reynolds number is a dimensionless quantity that is defined as the ratio of inertial to viscous forces. It is the decisive parameter for the flow regime.

The mixing efficiency of static mixers in laminar flow is analysed, for example, by forcing epoxy resins of various colours which have been premixed with hardener into the mixing section and subsequently curing them. The hardened strand can then be cut into slices in order to investigate what goes on inside the mixer. The sections obtained from the slices show that the number of layers increases rapidly with the length of the mixer; the layer thickness decreases at the same time while the homogeneity increases. Similar sections can also be represented nowadays using CFD calculations (refer to Figure 1).

Open wall area

For many years now, various attempts have been made to improve the mixing intensity of the CSE-X® mixer. A degree of success has been achieved by varying the number of mixing bars, for example, or the geometric structure.

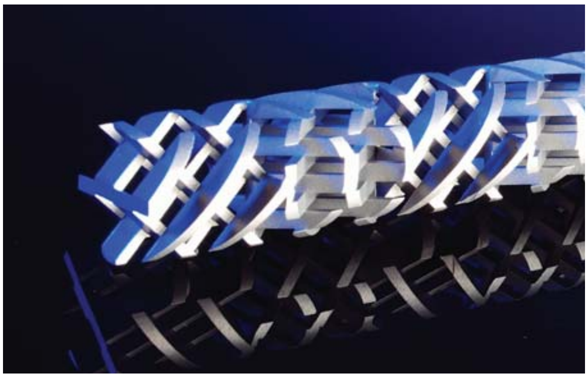

Fig. 2 CSE-X/4 and CSE-X/8 mixing element

An answer was needed to the following question: Is layer growth in the CSE-X mixer determined by the number of bars or is it the open ducts between the bars that are responsible?

If the open ducts are the culprit, one remedy could be to reduce the number of bars from 8 to 6 and at the same time open the wall area of the mixer tube. In this case the mixing efficiency should remain constant.

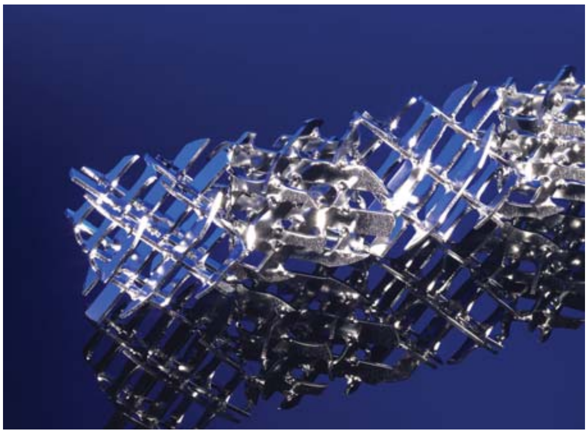

Fig. 3 CSE-X mixer with open wall area

Measuring homogeneity

The success of a mixing process can be quantified if a measure exists for the state of the mixture and this measure can be derived from locally determined quantities (e.g. temperature, concentration, electrical conductivity) by means of photometric analysis (FIP), laser induced fluorescence (LIF) or a CFD calculation, etc. [1]. If this data is available for the flow area, the mixture can be evaluated from a statistical point of view.

In the world of static mixing technology the variation coefficient COV has become established as the measure of mixing quality because in practice it is the final state of a mixture as a function of the concentration that matters. The smaller this quotient, the more homogeneous the mixture.

The following quantities have an influence on the mixing quality of a homogeneous mixture:

$$COV = f\left(Re, Fr, We, Sc, \frac{\eta_1}{\eta_2}, \dot{\gamma}, \bar{X}, \frac{L}{D}, Typ\right) \quad \text{Eq. 2}$$

In the case of highly viscous, soluble fluids, the dimensionless numbers Re, Fr, We and Sc are insignificant and can be disregarded assuming the fluids have a similar density and the differences in viscosity are only minor. In a first approximation for Newtonian laminar flow the above equation thus becomes:

$$COV = f\left(\bar{X}, \frac{L}{D}, Typ\right) = \frac{\sigma}{\sigma_0} \cdot \sqrt{\frac{1}{\bar{x}} - 1)} \quad \text{Eq. 3}$$

Since the mixture now depends solely on the concentration, the mixer geometry and the length, the variation coefficient can be represented as a function of concentration.

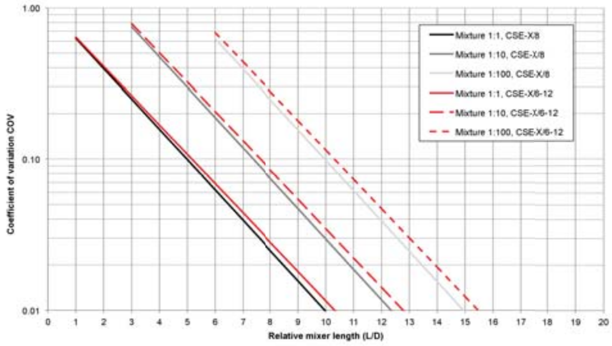

Fig. 4 Coefficient of variation COV of the Fluitec CSE-X and Fluitec CSE-X/6-12 mixers (adapted to the conductivity method [3], [2])

Figure 4 shows how the two mixer geometries result in almost identical mixing efficiency. The suspicion that layer growth is determined not by the number of bars but by the number of open ducts is confirmed. Opening the wall area is conducive to efficient mixing and the residence time range is relatively narrow. No wall effects so far have been observed in the CSE-X/6-12.

Pressure drop in laminar flow

The pressure drop must be overcome by means of conveying devices such as pumps, extruders or blowers. It can be described for Newtonian fluids using the following equation for the laminar flow regime:

$$\Delta p_l = NeRe \cdot \eta \cdot w \cdot \frac{Le \cdot Me}{D^2} \quad \text{Equation 4}$$

In the laminar flow regime the Newton number is inversely proportional to the Reynolds number, i.e. NeRe = constant. The NeRe number of the CSE-X/8 mixer is between 1200 and 2400 depending on the width of the bars. Surprisingly, measurements with the new Fluitec mixer have yielded NeRe numbers as low as 570 to 700. In other words, the CSE-X/6-12 mixer reduces the pressure drop by up to 50% without compromising mixing efficiency.

Example 1

A PET prepolymer is matted with titanium dioxide before being converted to film. The mixer must be installed in an existing plant. The length available for installation is L < 1.5 m and the maximum pressure drop must not exceed 15 bar. The TiO_2 needs to be mixed in homogeneously.

Additive containing TiO_2

$\dot{V}_1$ = 0.025 m^3 h^{-1} *TiO_2* content, x_1 = 500 gTiO_2/l

Viscosity η = 250 Pas

PET-prepolymer

$\dot{V}_2$ = 2.5 m^3 h^{-1}, viscosity η = 250 Pas

This results in the following mean concentration:

$$\bar{X} = 500 \cdot \frac{\dot{V}_1}{\dot{V}_1 + \dot{V}_2} = 500 \cdot \frac{0.025}{0.025 + 2.5} = 500 \cdot 0.01 = 4.95 \frac{g\,TiO_2}{l}$$

ΔXmax = +/- 0.5 g TiO2/l should be measured at the mixer outlet (Gaussian or normal distribution +/- ΔXmax = 2σ).

$$\Delta X_{max} = 2 \cdot \sigma \rightarrow \sigma = \frac{\Delta X_{max}}{2} = 0.25\ g\ TiO_2$$

The following variation coefficient is required here:

$$COV = \frac{\sigma}{\bar{X}} = \frac{0.25}{4.95} = 0.05$$

A minimum number of 12 elements can be estimated from Figure 4 for a concentration of 0.01 (1:100 mixture) and a COV of 0.05. Equation 4 yields the following pressure drop (1 bar = 10^5 Pa) for a CSE-X/6-12 DN100 mixer (D,Le = 0.105 m, w = 0.079 m s^{-1}, ε = 0.93, NeRe = 650):

$$dp = 650 \cdot 250 \cdot 0.079 \cdot \frac{0.105 \cdot 12}{0.105^2} = 14.7 \cdot 10^5\ Pa = 14.7\ bar$$

The value for the CSE-X/8 mixer is as follows (D,Le = 0.13 m, w = 0.053 m s^{-1}, ε = 0.91, NeRe = 1200):

$$dp = 1200 \cdot 250 \cdot 0.053 \cdot \frac{0.13 \cdot 12}{0.13^2} = 14.7 \cdot 10^5\ Pa = 14.7\ bar$$

A comparison of the lengths gives the following result:

$$L_{CSE-X/8} = 12 \cdot 0.13 = 1.56\ m, L_{CSE-X\ neu} = 12 \cdot 0.105 = 1.26\ m$$

$$\tau_{CSE-X/8} = \frac{1.56}{0.053} \cdot 0.91 = 26.8\ s,\ \tau_{CSE-X\ neu} = \frac{1.26}{0.073} \cdot 0.93 = 16.0\ s$$

A comparison of the residence times in the mixers shows that these times can be shortened by 40%.

Example 2

When polymer melt is extruded, a different temperature profile is produced in the melt stream. This profile depends on the type of screw as well as on the output. The temperature differential accordingly gives rise to significant quality variations in the end product. Errors due to inadequate homogenisation in the plasticating unit can be eliminated thanks to the CSE-X mixer.

A melt stream exhibits the following temperature difference at the mixer inlet:

Polystyrene PS MFI 3 - 4, flow rate 0.5 m^3 h^{-1},

T_{max} = 250°C, T_{min} = 230°C

Mean temperature T_m = 240°C

(inhomogeneous mixture 1:1 mixture)

$$\Delta T_0 = 20°C \rightarrow 2 \cdot \sigma_0 \rightarrow \sigma_o = \frac{\Delta T_0}{2} = 10°C$$

Fig. 5 CSE-X melt mixer for the extrusion process

The required temperature difference should be a maximum of +/- 3°C.

$$\sigma = \frac{\Delta T_{max}}{2} = \frac{3°C}{2} = 1.5°C$$

This results in a COV of:

$$1:1 \rightarrow \bar{X} = 0.5 \rightarrow COV = \frac{\sigma}{\sigma_0} \cdot \sqrt{\frac{1}{\bar{X}} - 1} = \frac{1.5°C}{10°C} = 0.15$$

A minimum number of approximately 4 elements can be estimated from Figure 4 for a concentration of 0.5 and a COV of 0.15. Various measurements have revealed that the temperature differences downstream of the mixer are slightly smaller in reality because this calculation ignores the effect of conduction.

Polymers generally have pseudoplastic (non-Newtonian) properties, i.e. their viscosity η is not constant but changes with the shear rate. The shear rate is calculated as the difference in flow velocity between two adjacent fluid layers in relation to the distance between these layers. It can be calculated for static mixers as follows:

$$\dot{\gamma} = \frac{k \cdot w}{D} \qquad \text{Equation 5}$$

Equation 5 yields the following shear rate for a CSE-X/6-12 SM75 melt mixer (D,Le = 0.0682 m, w = 0.04 m s^{-1}, NeRe = 670, k = 38):

$$\dot{\gamma} = \frac{k \cdot w}{D} \approx \frac{38 \cdot 0.04}{0.0682} \approx 22.3\ s^{-1}$$

The viscosity graph in Figure 6 shows a mean viscosity of approximately 1220 Pas for the mean shear rate at 240°C.

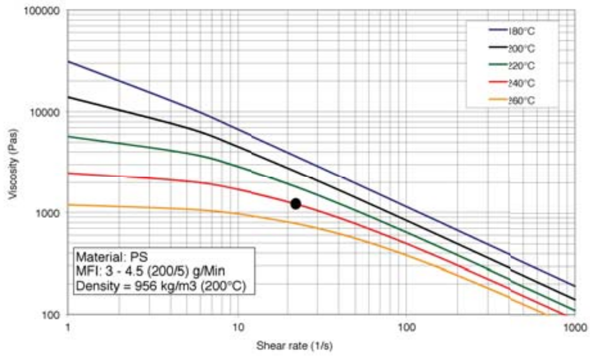

Fig. 6 Viscosity graph for polymer melt PS

According to equation 4, this results in a pressure drop of:

$$dp = 670 \cdot 1220 \cdot 0.04 \cdot \frac{0.0682 \cdot 4}{0.0682^2} = 19.2\ bar$$

Example 3

A water based dye is dosed into a highly viscous sugar solution and mixed homogeneously. A mixture is considered to be homogeneous ifs a variation coefficient is between 1% and 5%.

Required COV = 1%, mixer ø = 41.9 mm
Empty tube velocity w = 0.02 m s^{-1}
Water based additive
$\dot{V}_1$ = 1 l h^{-1} dye, viscosity η = 1 mPas
Sugar solution
$\dot{V}_2$ = 100 l h^{-1}, viscosity η = 35'000 mPas

$$\bar{X} = \frac{\dot{V}_1}{\dot{V}_1 + \dot{V}_2} = \frac{1}{100+1} = 0.01$$

The two works by Streiff [5] [6] explain how the number of mixing elements required can be calculated as 19.5 (or 20 for an 8-bar mixer). The pressure drop for a CSE-X/8 mixer can be calculated as follows according to Equation 4 with an NeRe number of 1450:

$$dp = 1450 \cdot 35 \cdot 0.02 \cdot \frac{0.0419 \cdot 20}{0.0419^2} = 4.85\ bar$$

In contrast to the CSE-X/8 mixer, the Fluitec CSE-X/6-12 mixer has been observed to be dependent on the sheare rate in high / low-viscosity mixing processes. This dependency is represented in Figure 7 for a viscosity ratio of 35'000.
The mean shear rate must be calculated in order to specify the number of mixing elements required. This rate can be shown as follows:

$$\dot{\gamma} = \frac{k \cdot w}{D} \approx \frac{38 \cdot 0.02}{0.0419} \approx 18.1\ s^{-1}$$

A minimum number of 18 elements can be estimated from Figure 7 for a concentration of 1% and a shear rate of 18.1 s^{-1}. Equation 4 yields the following pressure drop for a CSE-X/6-12 DN40 mixer (D, Le = 0.0419 m, w = 0.02 m s^{-1}, NeRe = 700):

$$dp = 700 \cdot 35 \cdot 0.02 \cdot \frac{0.0419 \cdot 18}{0.0419^2} = 2.11\ bar$$

Once again, the superiority of this mixer is striking, especially when the pressure drop is identical. If a CSE-X/6-12 mixer with a diameter DN30 is chosen (D, Le = 0.031 m, w = 0.037 m s^{-1}, NeRe = 650), the shear rate is 45 s^{-1}, so that 17 mixing elements are sufficient to ensure homogeneous mixing.

$$\dot{\gamma} = \frac{k \cdot w}{D} \approx \frac{38 \cdot 0.037}{0.031} \approx 45.4\ s^{-1}$$

$$dp = 650 \cdot 35 \cdot 0.037 \cdot \frac{0.031 \cdot 17}{0.031^2} = 4.61\ bar$$

Summary

Mixing processes involving fluids with a viscosity ratio greater than 1:1000 can generally be described as problematic. In the past, only the CSE-X/8 mixer has been capable of performing them successfully. This makes the ability of the CSE-X/6-12 mixer to master these challenges all the more impressive. The efficiency of the CSE-X/6-12 is easily superior to that of conventional X mixer models. The properties of the CSE-X/6-12 mixer can be summed up simply as follows:

If the mixing efficiency is the same:
- The pressure drop in the mixer is around 50% smaller.

If the pressure drop is the same:
- The mixer can be designed one diameter smaller.
- The residence time is about 40% shorter.

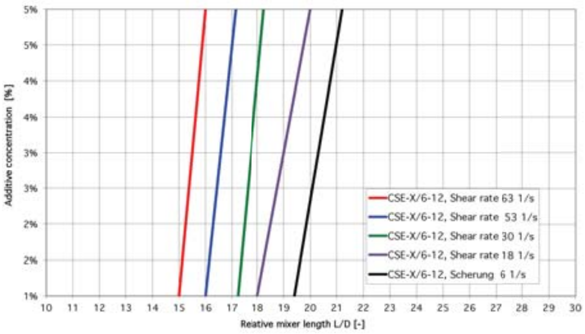

Fig. 7 Mixing efficiency of the new CSE-X mixer for a viscosity ratio of 35'000

List of symbols

	Designation / SI unit
COV	Variation coefficient [-], [%]
d_h	Hydraulic diameter [m]
dp	Pressure drop [Pa, bar]
D	Diameter [m]
k	Shear factor [-]
Le	Length of mixing element [m]
Me	No. of mixing elements [-]
$NeRe$	Resistance factor [-]
Re	Reynolds number [-]
$\dot{V}_1$, $\dot{V}_2$	Volume flow [m3 s^{-1}]
w	Empty tube velocity [m s^{-1}]
$\bar{X}$	Arithmetic mean, concentration [-]
ΔT	Temperature difference [°C]
ΔX	Concentration difference [-]
τ	Residence time [s]
ε	Void volume [-]
η	Dynamic viscosity [Pas]
ρ	Density [kg m^{-3}]
σ	Standard deviation [-]
$\dot{\gamma}$	Shear rate [s^{-1}]

Literature:

[1] Grosz-Röll, F.: Aufbereitungs-Technik 20 (1979)
[2] Streiff, F.: Chem.-Ing.-Tech. 52 (1980) Nr. 6, S. 520 – 522
[3] Pahl, M., Muschelknautz, E.: Chem.-Ing.-Tech. 52 (1980) Nr. 6, S. 285 – 291
[4] EP 2 286 904 B1.; Statische Mischvorrichtung für fliessfähige Stoffe
[5] Streiff, F. Verfahrenstechnik 34 (2000) Nr. 1-2
[6] Streiff, F. Mischen von Kunststoffen und Kautschuk, VDI-Verlag, 1993