Recent Innovations in Turbulent Mixing with Static Elements

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Abstract: Static Mixer consists of a number of stationary mixing elements inserted along the direction of flow in a pipe. Each mixing element allows to divide the flow and to recombine it in a geometric sequence.

A lot of static mixers are now available, e.g. Sulzer SMV and SMI, Chemineer KM, the Kenics HEV. These products differ quite considerably and the construction have effects on the manufacturing costs and also on the costs for the inbuilt the mixers in a plant. These well known motionless mixers allow to obtain good performances but usually the mixing length necessary for obtaining the homogeneity is longer than 5-10 pipe diameters. Another important constrain is the maximum permissible pressure loss in the operation.

In the recent years, new products composed of a minimum number of elements, have been launched. These new products have a short inbuilt device length, they require a short mixing path and they have low pressure drops. This review analyzes the behaviour of these new innovative static mixers.

Keywords: Static mixer, Sulzer CompaX, computational modelling, mixing, turbulent flow.

INTRODUCTION

In industrial applications, typically, when mixing processes are required the equipment that is selected is a stirred tank. However, this is not the only choice that can be done. CompaX mixer described in the patent [1], is an evolution of the idea [2, 3] of using simple short three-blanded mixer for obtaining excellent mixing performances. In fact, mixing occurs, not only by mechanical agitation, but also in the pipelines connecting the existing tanks in the plant. Sometimes the pipe, especially if static mixers are inserted into, is the better place where mixing can occur [4]. This choice can allow to save money, because the investment cost necessary for a static mixer is always lower than that of a dynamic agitator and because, for some applications, it allows to save energy. In fact, is worth noticing that the only power required for static mixers applications is the external pumping power necessary to compensate the pressure drops through the mixer. Static mixers are continuous radial mixing devices and they allow to obtain, basically, a plug flow. As these devices are characterised by short residence time and little back mixing, they can be used when the residence time required by the operation ranges is in the order of seconds to minutes. Therefore, good performances can be especially obtained when fast blending is required, when a fast chemical reaction occurs or when long hold-ups, typically associated to the use of a stirred tank, have to be avoided. A lot of industrial applications can now be identified where static mixers are used: homogenization, dispersion, emulsifying, gas/liquid and liquid/liquid contacting, co-current mass transfer, heat transfer and chemical reaction. For interphase mass transfer applications, both agitated vessel and static mixers supply at the most a single equilibrium stage. Since static mixers have no moving parts they needs low maintenance costs and they have no sealing problems [4]. Therefore, in industrial practice, the main advantage of static mixers as compared with agitated tanks or dynamic in line mixers is their rapid mixing characteristics (small volume compared to stirred tanks) and the complete absence of sealing problems [5]. The above differences between dynamic mixers and motionless mixer allows to conclude that pipelines mixing can be suggested especially when:

- Plug flow is preferred to backmixing,
- Component feed rates are uniform,
- Short residence time is required,
- The continuous phase is a gas,
- The available space is limited,
- For high pressure applications,
- For continuous processes.

The differences between the mixing in a normal pipeline and in a pipeline equipped with a static mixer is apparent. In turbulent flow, static mixers create a higher degree of turbulence as compared to an normal pipe, thereby resulting in a higher degree of mixing dispersion and/or mass transfer. The key design parameters for turbulent applications are velocity and turbulent dissipation. An empty tube working in turbulent flow regime is the simplest static mixer, however it is necessary a length nearly equal to 100 pipe diameters for complete mixing (Hartung and Hiby [6], Tauscher and Streiff [7]). On the contrary, if static mixers are used, the complete mixing can be obtained with a length nearly equal to 4-6 diameters.

For absorption applications, static mixer are used in cocurrent contacting devices and their performances are usually better than that of other equipments as spray nozzles, Venturi scrubbers and random-packed columns [8]. Comparing static mixers to the other devices, the main

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advantages are the turndown and the versatility. If static mixers are compared to random packings a lower friction factor, due to a higher void fraction can be evidenced. The geometrical difference induces lower pressure drop and therefore lower power consumption. Moreover, in random packings the absence of radial mixing can induce channeling and therefore it can bring on in-homogeneities in concentration and temperature. While, static mixers, because of the special flow pattern, produce a uniform distribution of the concentrations and temperature over the whole flow cross section. The main difference between static mixers and jet or Venturi scrubbers is due to the place where the energy is dissipated that, for two-phase applications, is strictly linked to the value of interfacial area: high dissipated energy usually induces high interfacial area. For jet or Venturi equipments the energy dissipation is localised, so in that part of the apparatus is contained the highest portion of the interfacial surface involved into the mass-transfer phenomena. When static mixers are used the density of dissipated energy is constant and therefore the interfacial surface is well distributed across the section [8].

GENERAL DESCRIPTION OF A MOTIONLESS MIXER AND APPLICATIONS

The intensive use of static mixers in the industrial processes is dated around the 1970s even if the first patent is much older. Indeed, Sutherland [9] in 1874 patented a multilayer motionless mixer to mix air with gaseous fuel. A complete analysis on the evolution of static mixers patents has been recently published by Thakur *et al*. (2003) [10]. From the commercial point of view, it is important to know that nowadays more than 2000 US patents on the static mixers have been deposited and about 30 commercial models are currently available.

Thakur *et al.* (2003) [10], selected the more important manufacturers, whose extended list has been reported in Table **1**, and some industrial applications.

As pointed out in the introduction, a static mixer is formed by a series of elements inserted end-to-end in a pipe. The goal of each element is to divide and afterwards recombine the main flow in a geometric sequence. This sequence induces a strong mixing (e.g. of the main flow with an additive) and allows to obtain a high degree of homogeneity downstream the mixer, see Fig. (**1**).

A lot of different static mixers have been developed for turbulent and laminar applications therefore the identification of the typical mixer for each specific application is not straighforward. Etchells and Meyer [4] suggested a simple table that a customer could use for the mixer choice, that for the convenience of the reader is shown in Table **2** (e.g. for blending of highly viscous miscible fluids in laminar regime the suggested mixers are SMX or SMXL).

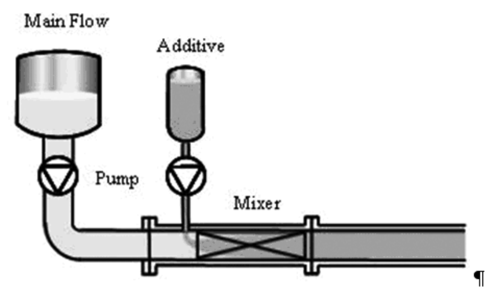

Fig. (1). A schematic diagram of the mixer.

Table 1. Some of the Most Important Commercially Available Static Mixers

Company	Products	Web site
Chemineer-Kenics	Kenics mixer (KM), HEV	http://www.chemineer.com/
Sulzer Chemtech	SMF, SMN, SMR, SMRX, SMV, SMX, SMXL, SMI, KVM	http://www.sulzerchemtech.com/
Charles Ross & Son	ISG, LPD, LLPD	http://www.mixers.com/
Wymbs Engineering	HV, LV	Not available
Lightnin	Inliner Series 45, Inliner Series 50	http://www.spxprocessequipment.com/
EMI	Cleveland	http://www.capitalprocess.com/emi-inline.htm
Komax	Komax	http://www.komax.com/
Bran and Luebbe	N-form	http://www.spxprocessequipment.com /sites/branluebbe/global/eng/products/ pdf_files/4_7_Static_Mixers.pdf
Toray	Hi-Toray Mixer	Not available
Prematechnik	PMR	http://www.prema-service.de
UET	Heliflo (Series, I, II and III)	http://www.uetmixers.com
Noritake	N10, N16, N26, N60	http://www.noritake.co.jp/eng/eeg

Table 2. A Guideline for Static Mixer Selection [4]

Basic Unit Operation	Fluids	Application	Mixer
Narrow residence time distribution (laminar regime)	Highly viscous fluids	Plug flow laminar	SMX/SMXL
Laminar flow heat transfer	Highly viscous heat sensitive	Heat transfer with viscous liquids	SMXL/SMR
Laminar flow mixing/blending	Highly viscous miscible	Blending laminar liquids	SMX/SMXL
	High and low viscosity, miscible	Mixing high/low viscosity liquids	SMX
Laminar flow dispersing	High and low viscosity immiscible	Dispersing high/low viscosity liquids	SMX
Turbulent flow dispersing	Liquid as continuous phase with gas	Mass transfer for dissolution of gases	SMV KMS
		Mass transfer with chemical reaction	SMV KMS
	Gas as continuous phase with liquid	Mass transfer for absorption	SMV
		Mass transfer with chemical reaction	SMV
		Vaporization	SMV
	Low viscosity immiscible liquids	Dispersing emulsifying	SMV KMS
		Mass transfer for extraction, washing	SMV KMS
		Mass transfer with chemical reaction	SMV KMS
Turbulent flow mixing/blending	Low viscosity miscible	Blending low viscosity fluids	KVM SMV HEV KMS
Narrow residence time distribution	Low to medium viscosity fluids	Plug flow low viscosity fluids	SMV SMVP KMS

One of the most interesting new applications for the air pollution control is the use of static mixers in the catalytic DeNOx process (Selective Catalytic Reduction). For obtaining the ideal reaction conditions in the catalyst beds it is necessary to fully mix the ammonia and NOx as well as to obtain low radial gas temperature gradients. Fig. (**2**) shows the temperature gradients obtained by a CFD simulation of the upstream of a flue gas heater [11]. As can be observed temperature gradients at the inlet of the catalyst bed are very low. The experimental data, obtained at the Roxboro 1 plant station (USA) shows that the root mean square (RMS) in NH_3 concentration distribution is lower than 5%, the gas temperature distribution is less than $\pm$14°C from the mean temperature and that the pressure drops across the mixer not exceed 24 mm w.c. at the full load.

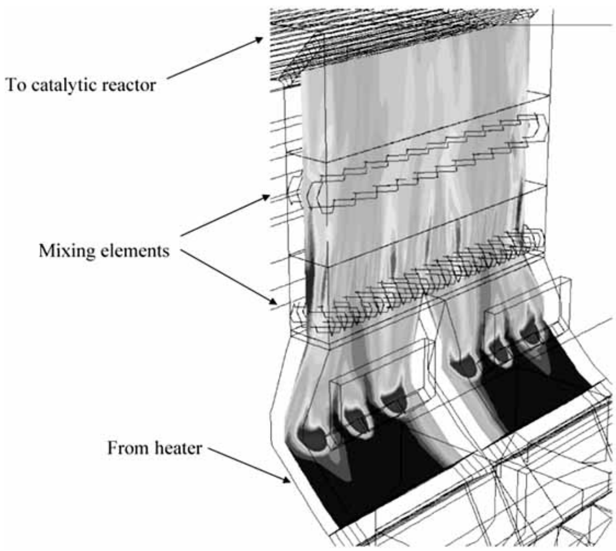

Fig. (2). Temperature homogenization upstream of a flue gas heater in a DeNOx process [8].

DESCRIPTION OF THE CompaX STATIC MIXER

In the following, the CompaX, a new product by Sulzer Chemtech, that is shown in the Fig. (**3**), will be analysed.

The mixer has been developed for mixing low viscosity fluids and all the necessary devices are contained in a pipelines which can be of several forms. The mixer is essentially formed by structured elements, which can be flat, folder or curved sheets, whose goal is to obstacle the primary flow inducing a first order mixing phenomenon. The surface and/ or the edges of these obstacles are modified to induce a second order mixing phenomenon which coupled with that of the first order allows to improve the homogenization quality. In Fig. (**4**), a schematic diagram of the new mixer is shown.

The inventors pointed out that the presence of the second order phenomenon is not negligible because it allows to reduce both the radial and the axial inhomogeneities. Moreover, compared with a mixer formed by a single short mixing element, the CompaX mixer allows to eliminate some drawbacks as the periodic concentration fluctuations in the pipe at fixed observation positions.

Fig. (3). CompaX vortex static mixer (courtesy of Sulzer Chemtech).

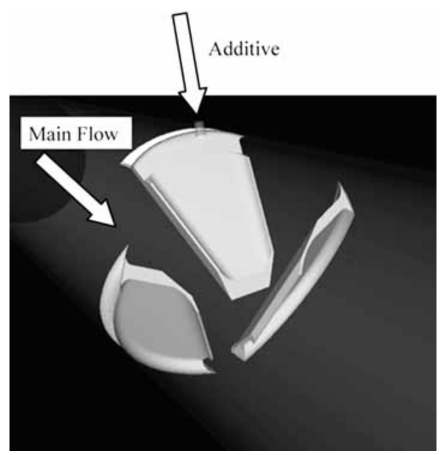

Fig. (4). A schematic diagram of the CompaX mixer.

The strong influence of the second order mixing phenomenon seems to be confirmed also by CFD simulations. Figure (**5**) shows the results by Fleischli and Suhner [12] considering air at standard conditions as the working fluid. The simulation results clearly show that the additive, that is inserted in the pipe from the inlet pipe shown in the upper part of the figure, in few diameters is dispersed in the main flow. Figure (**6**) shows as the additive can be dispersed along the pipelines, the figure has to be consider only from a qualitative point of view. However, it is worth noting that a uniform distribution is achieved at 3 D downstream.

The manufacturer published not only CFD simulations but also some experimental data of the coefficient of variation CoV. It is worth noting that, as a general rule, a CoV-value of 5% is considered to be coincident with a well mixed condition, and a value of 1% corresponds to very well mixed flow [4].

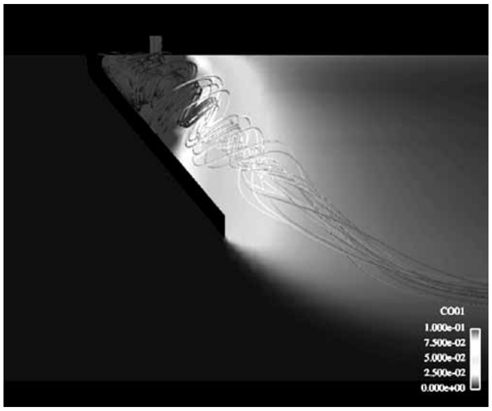

Fig. (5). A detail of the CFD simulation performed by Fleischli and Suhner [12] (STAR-CD, Standard k-ε model, incompressible flow, Conditions: Air, P = 1 bar, T = 20°C, main flow = 10m/s, additive = 23m/s, flow ratio 1:300).

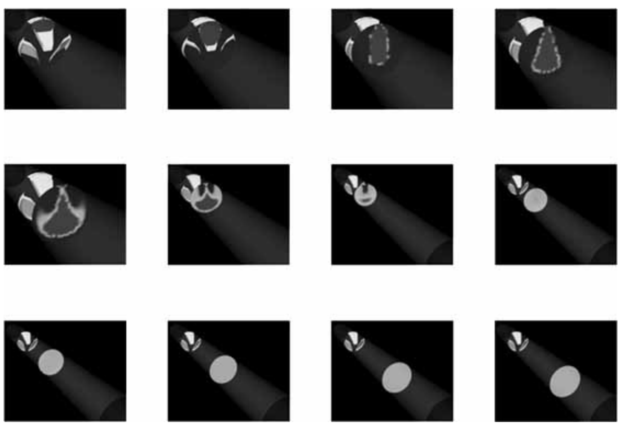

Fig. (6). Evolution of the additive dispersion along the pipeline .

The coefficient of variation can be evaluated as:

$$CoV = \left[\frac{\sum_{i=1}^{N}\left(\frac{c}{c_i}-1\right)^2}{N-1}\right]^{0.5} \cdot \frac{1}{c_{mean}},$$

where:

c is the average measured concentration of the additive,

c_{mean} is the theoretical mean concentration,

c_i is the local concentration of the additive at the it measurement position,

N is the number of positions where concentration is measured.

Fig. (**7**) shows the experimental data of CoV as a function of the dimensionless length, L/D. In this figure, three sets of data have been shown, relevant to different ratio between the additive stream and the main ones (mixing ratio).

Fig. (**7**) shows that the mixing ratio weakly influences the coefficient of variation and that a well mixed section can be found about 3 D downstream the mixer and a very well mixed section is at about 12 D. The experimental data shown in Fig. (**7**) have been used for identifying the correct turbulence model that has to be used for simulating the behaviour of CompaX mixer. Figure (**8**) shows the experimental data with mixing ratio 1:2000 and two computer trends obtained using the standard k-ε model and the cubic

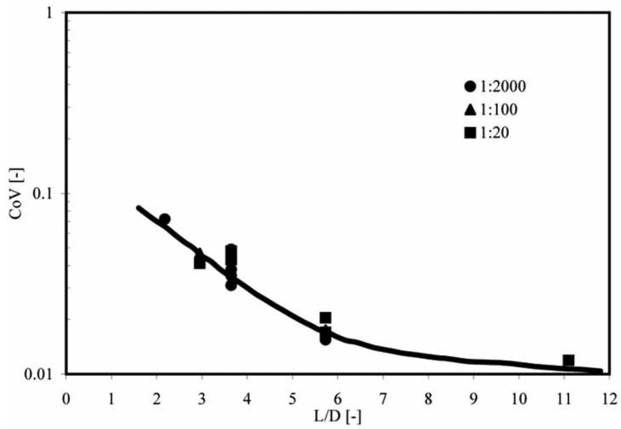

Fig. (7). Mixing in a pipe after the fluid outlet from the CompaX mixer. Air CO_2 system, pipe diameter 6” Laser, test method induced fluorescence (LIF).

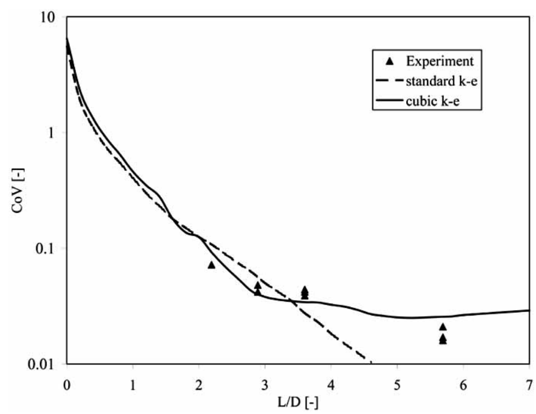

Fig. (8). Mixing in pipe after outlet of the CompaX mixer comparison between experimental data and CFD results.

k-ε turbulence model. The figure shows that good prediction of the mixer performances can be obtained with both the models up to a downstream distance of about 4 diameters, for longer distance the cubic k-ε seems to predict the experimental data with higher accuracy than the standard k-ε. Moreover, it is necessary to notice that, at L/D=5.8, the coefficient of variation is really low and therefore experimental errors can affect the experimental datum. This computational results should be deeply analysed in the next future. In fact, it is well known that the use of standard k-ε model cannot account for the influence of streamline curvature on the turbulence in the flow [4] and that it could induce over-prediction of turbulent mixing. Nevertheless, before adopting the cubic k-e model as a standard for simulating the behaviour of the CompaX mixer, it should be necessary to have more details on the cubic turbulence model used in the CFD simulations shown in Fig. (**8**) and also it should be interesting to compare the CFD results obtained with the cubic k-ε with the results obtained using other available turbulence models.

The manufacturer gives not only experimental data on the coefficient of variation but also experimental data on the

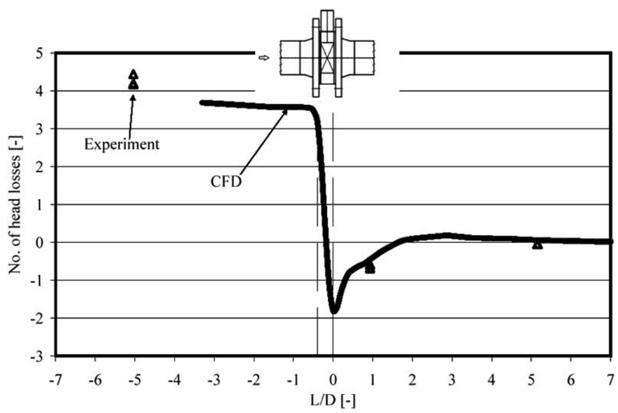

Fig. (9). Pressure drop across the CompaX mixer, experimental and computed trends. Air system, pipe diameter 2´´, standard k-ε model, incompressible flow, unstructured grid.

pressure drop; that is the second important parameter that it is necessary to take into account for a correct design of the apparatus. Figure (**9**) shows both the experimental data and the computed trend obtained by CFD simulations. It is interes-ting to notice both the low values of the experimental num-ber of head losses and that CFD simulations, performed using standard k-ε model allow to predict with high accuracy the experimental data.

From a CFD analysis, it is possible to obtain not only macroscopic parameters, as pressure drops, but also a detai-led fluid-dynamic information. In the Fig. (**10a**) the velocity distributions at the mixer outlet section and in other two sec-tions located at 1 diameter and five diameters downstream are shown. It can be noticed that the effect of the mixer on the fluid velocity is weak 5 diameters downstream the mixer and it is negligible after 6 diameters, as the analysis of the Fig. (**10b**) shows.

DESIGN GUIDELINES

The manufacturer supplies some general rules for the design of the CompaX mixer [12]. Supposing that the main flowrate flowing in the mixer is known, the designer has to decide the maximum value of the pressure drop in the mixer, afterwards the nominal value of the CompaX diameter can be identified with the graphic shown in Fig. (**11**).

The designer, besides to the mixer diameter, has to select the hole diameter for the additive flowrate. The choice can be done using the graphic reported in Fig. (**12**), if the hole diameter is greater than the maximum size shown in Table 3, the designer has to increase the nominal diameter of the mixer.

Using the graphics shown in Figs. (**11**) and (**12**) it is possible to choose the geometrical characteristics of the mixer and to estimate the pressure drops that can be expected. To evaluate the mixing performances of the new product the shortcut way, shown in Fig. (**13**), has been suggested.

This approach is strictly valid a) if the Reynolds number of the main flow is higher than 2300, b) if the ratio between the maximum and the minimum viscosity of the two fluids is

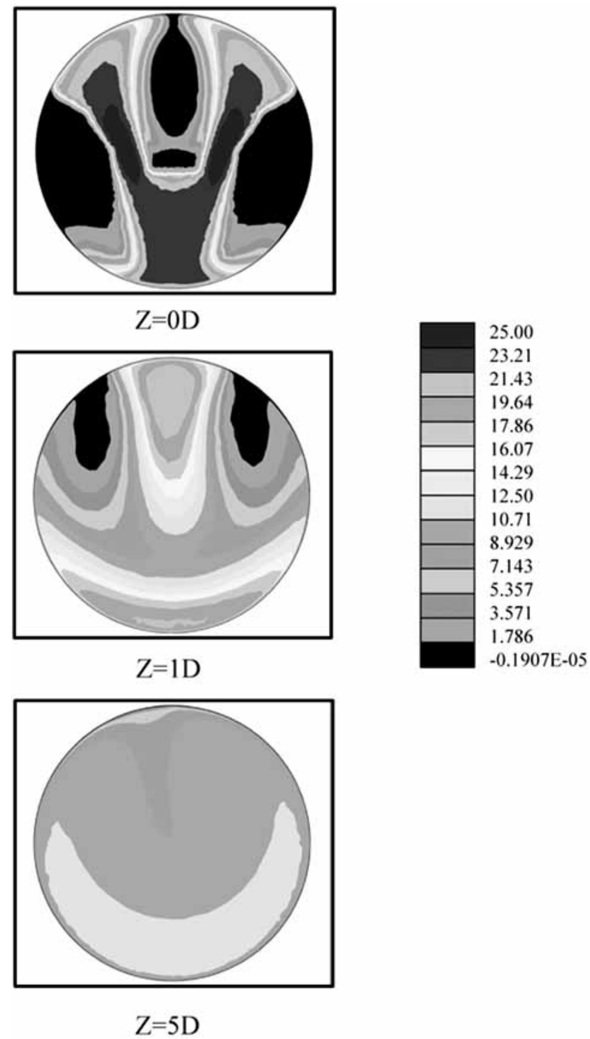

Fig. (10a) Velocity distributions at 0, 1 and 5 diameter downstream the mixer. Air system, pipe diameter 2".

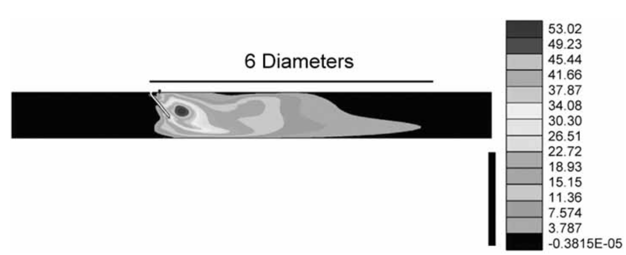

Fig. (10b). Turbulent kinetics energy downstream the mixer. Air system, pipe diameter 2".

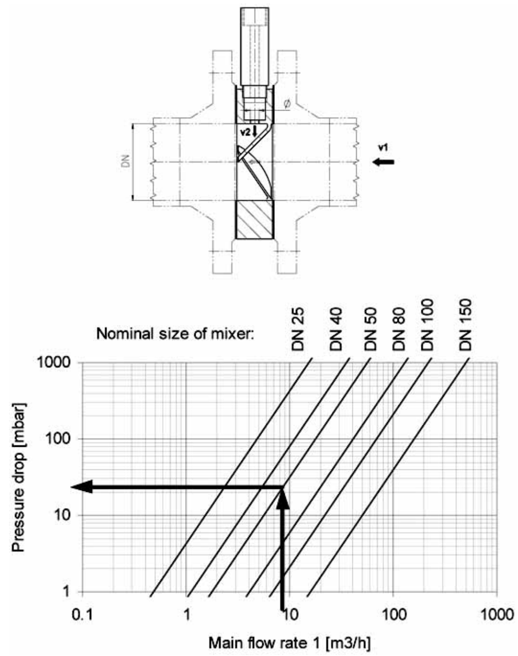

Fig. (11). Suggested guidelines for selecting the nominal diameter of the mixer.

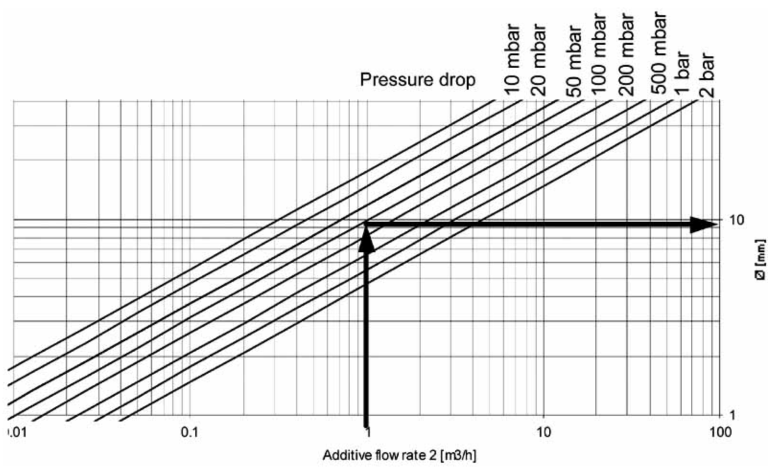

Fig. (12). Suggested guidelines for selecting the hole diameter for the additive flowrate.

lower than 100, and c) if the $\frac{\Delta\rho}{\rho_1} < \frac{v_1^2}{200\phi}$, where $\Delta\rho$ is the absolute value of density difference between the additive and the main flow, ρ_1 is the density of the main flow, v_1 is the mean velocity of the main flow and ϕ is the hole diameter for the additive flowrate.

COMPARISON WITH THE OTHER AVAILABLE PRODUCTS

Before to introduce a comparison of the CompaX mixer to other commercially available mixers, it is necessary to point out its targets. From the mechanical point of view, it is characterized by a simple design and simple installation

Table 3. The Maximum Hole Diameter for the Additive Flowrate as a Function of the Nominal Diameter of the Mixer

DN	ϕmax
[mm]	[mm]
25	10.5
40	10.5
50	10.5
80	19
100	25
150	34

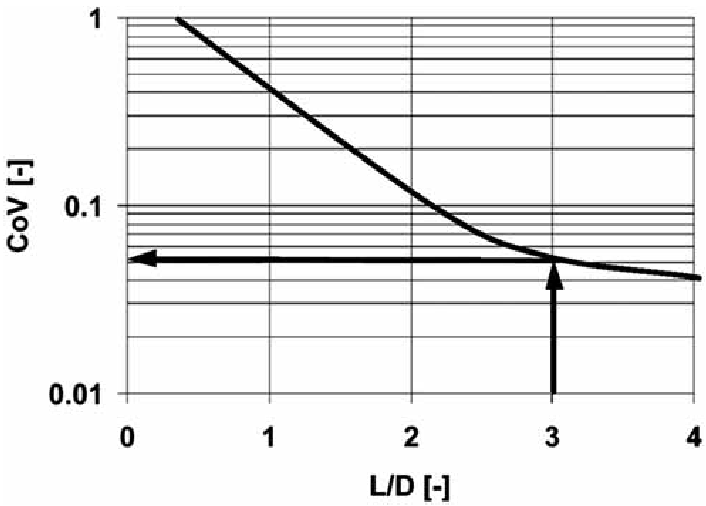

Fig. (13). Suggested guidelines for evaluating the coefficient of variation as a function of the pipe dimensionless length.

procedures because only a mixing element is necessary, which does not need housing or flanges, and only a single dosing port is required. It can be used both in new and revamping plants because it needs a really short installation length. From the operative point of view, a short mixing length and acceptable pressure drop have been guaranteed. Moreover, for process where clogging is possible CompaX mixer, because of its simple mechanical design, it allows to simplify the cleaning operations. The investment cost could be reduced if CompaX mixer is installed because it is characterised by a good price/performance ratio.

Fig. (**14**) shows a comparison between some mixers commercially available [12].

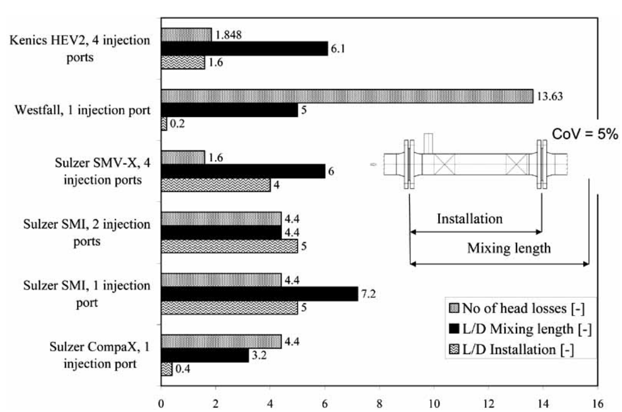

Fig. (14). Comparison of mixer efficiencies. Experimental conditions: CoV < 0.05, V_1/V_2 ~ 1000, Re > 10'000.

It is worth noticing that if the mixing efficiency is the same, CoV=5%, the Compax mixer shows the lowest mixing length, 3.2 D, the Westfall mixer shows the lowest installation length but really high pressure drop (the number of the head losses is 13.63 while for Compax is 4.4). Lowest pressure drops are achieved using multiple injection ports (e.g. Sulzer SMV-X and Kenics HEV2 with four ports show 1.6 and 1.848 head losses respectively) but CompaX mixer, that needs of a single injection port, shows an interesting value of head losses, 4.4, equal to the Sulzer SMI type.

CURRENT & FUTURE DEVELOPMENTS

The analysis of the available documents on the CompaX mixer shows that it can be an interesting product when strict design conditions about mixing efficiency, mixing length, installation length and pressure drops are required. Unfortunately, nevertheless static mixers are widely used, few data regarding their performances are available in the open literature. In the future, it should be important to test its performances also in independent laboratories. In fact, in a recent work [13], performed on other mixers, it has been shown that manufacturer correlations could fail in the prediction of some mixing characteristics.

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