Pressure Drop in Motionless Mixers

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A motionless mixer consists of a straight pipe or transfer tube containing the mixing elements that are used to cut, fold, twist, and re-combine the mixing fluid. The number of elements and their shape required in any application depend on the complexity of the mixing process. The objectives of this study are to develop new motionless mixers and to perform the experimental investigation of pressure drop in order to evaluate the performance of the new ones. Glycerin is used as a mixing fluid. Pressure drop is measured using a hydraulic manometer and correlations of friction factor are proposed as a function of Re. The friction factors of Sulzer SMX mixer are in qualitative good agreement with the published data. On the average, the friction factors of SSC and YNU mixers are about 36% lower than and 6% higher than that of the Sulzer one.

Key Words : Motionless Mixer, Mixing Element, Pressure Drop, Friction Factor, Laminar Regime

Nomenclature

D : Mixer diameter
f : Friction factor
L : Total length of mixer
ΔP : Pressure drop
Re : Reynolds number
v : Velocity
Z : Pressure drop correlation factor
ρ : Density
μ : Viscosity
ε : Void fraction of mixer element

Subscripts

et : Empty tube
sm : Motionless mixer

1. Introduction

Mixing has been used by man from time immemorial in preparation of food and drink, and belongs to the classical unit operations used in many branches of industry. Moreover, in the chemical process, this mixing technology is of special importance to carry out chemical reaction. The solutions and mixtures are prepared in such a way that the reagents have a suitable form for reaction. During the reaction process, the mixing operation must ensure that the reagents stay in close contact with each other. Especially, this is particularly important when the reagents have a different aggregate state. In connection with increasing volume of chemical production continuous processes are increasingly significant, which presents special requirements with respect to the corresponding apparatus. Mixing can be performed continuously in a mechanical agitator or directly in a pipeline. The latter way of mixing usually adopts in-line mixers or motionless mixers.

Motionless (also called in-line or static) mixers have found a large range of applications, including blending, reaction, dispersion, heat transfer and mass transfer. All the motionless mixers have in common a straight pipe or transfer tube containing the mixing elements that are used to cut,

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fold, twist, and re-combine the process fluid as shown in Fig. 1. The operations virtually ensure uniformity in composition, concentration, viscosity and temperature. The elements improve mixing, heat transfer and mass transfer efficiency compared to that achieved in an empty pipe. The energy for mixing is obtained from the pressure loss as the process fluid flows around the mixing elements. Mixing by means of the motionless mixers offers a number of advantages as compared with classical dynamic mixers (Sir and Lecjaks, 1982) : (i) it can be installed in the existing pipeline or tube, (ii) it involves no rotating elements such as shafts and bearings, and needs no extra seals, (iii) it needs lower investment and operating costs, (iv) it is noiseless and suitable for explosive environment, (v) it has lower shear forces so that the product is not damaged during the processing. In the mechanical agitators (Fig. 2), longitudinal and transverse distribution of materials to be mixed can be obtained by means of moving blades. In this apparatus, however, stagnant zones can exist and material may ride on blades and be kept out of the mixing region. Also, high velocity blades may be ineffective since they create an isolated hole in the mass without producing any circulation.

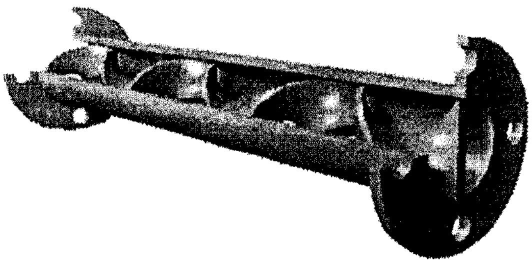


Fig. 1 An example of motionless mixer; Kenics mixer

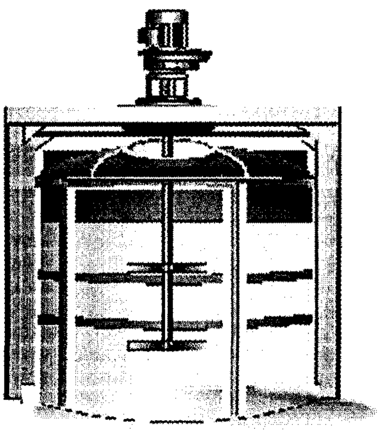


Fig. 2 An example of mechanical agitator

Published data on the motionless mixers are of two sorts: papers and manufacturers bulletins providing general information about the respective products, and research reports dealing mostly with the pressure drop and homogenization efficiency. A wide variety of motionless mixer designs are reported in the literature. However, only few models are actually used in industry (Pahl and Muschelknautz, 1982 ; Cybulski and Werner, 1986 ; Myers et al., 1997). Most studies determine design parameters, i.e. pressure drop (head loss), heat and mass transfer coefficients, mixing efficiency, etc. These parameters are global, because they are measured before and after mixers. Therefore, the mixers can be treated as black boxes. In some cases, no real understanding of how the mixers affect the parameters is obtained. However, the parameters obtained can be used directly in process design. The performance of a given mixer is tested with several criteria. In general, motionless mixers have been first compared on the basis of the pressure drop generated for a given flow rate and mixer diameter. The mixing efficiency parameters have been introduced by variance of concentration, the residence time distribution, the chaotic nature of the flow and the type of deformation inducing mixing.

Pahl and Muschelknautz (1982) provided the correlations for pressure drop of laminar and turbulent flow with several motionless mixers. Also they reported that the mixing effect in motionless mixers with laminar flow was achieved by constructed product guides (holes), cutting and turning (helices), displacement and distortion (crossing channels), dividing and spreading (oblique strips). Sir and Lecjaks (1982) investigated pressure drop to find the dependence of the drag coefficient of the mixer within a broad range of the Reynolds number, to determine the regions of laminar, transition and turbulent flow in the mixer, and to judge the effect of element number and pipe diameter on drag coefficient. Shah and Kale (1991) and Chandra and Kale (1992) presented the empirical correlations between friction factor and generalized Reynolds number for non-Newtonian inelastic and viscoelastic fluids. Their correlations were developed for the static mixers of different designs and sizes. They demonstrated that the viscoelastic fluids exhibited higher pressure drop compared to the inelastic fluids. Li et al. (1996) investigated pressure drop in a Sulzer SMX motionless mixer with both Newtonian and rheologically complex fluids. A correlation had been established between the friction fanning factor and the generalized Reynolds number.

Because of the complexity of the physical phenomena of mixing, no theory has been developed. Indeed, until recently, nothing has been published which might permit comparison of one design with another, and no method has been developed which permitted insights into the mixing phenomena of a given design. Unfortunately, only very limited data have been appeared in the study of motionless mixers. Especially, a deep understanding of the hydrodynamics is still lacking when geometrically complex elements are involved. In present study, new motionless mixers are developed and their performance is investigated by experiment.

2. Experimental Apparatus and Method

2.1 Motionless mixers and experimental apparatus

One of the first technically applied motionless mixers is twisted tape mixer (Kenics mixer) schematically shown in Fig. 1. The mixer has right and left-hand twisted elements. These elements are staggered so that each leading edge is at 90° of the trailing edge of the former one. This model is a popular mixer in North America for viscous, low Reynolds number applications. The other type (Sulzer SMX, SMV, SMXL) mixers that use more complicated elements have also been used for these applications and may be preferred in the European community (Jaffer and Wood, 1998). The mixing elements have been made from the intersecting bars or sheets welded together to form open channels as shown in Fig. 3. Sulzer SMX type of lamellar mixing elements splits the material into individual streams that meet other streams as they flow transversely through the element. Each element mixes principally in two dimensions and the elements are aligned at 90° to their neighbors to enable three-dimensional mixing (Bauman, 2001).

The motionless mixers used in this study have 40 mm diameter acrylic tubes being fitted with mixing elements. Eight-element SSC, YNU and Sulzer SMX mixing elements made of stainless steel are shown in Fig. 3. Each unit element has a diameter of 40 mm and a length-to-diameter ratio equal to one. The thickness of intersecting bars and of elliptic plates is 2 mm. The SSC and YNU elements are the new models designed in this study. In general, the smaller the passageways and the larger the fraction of cross section occupied by elements, the higher the pressure drop. The element of Sulzer SMX mixer is geometrically complicated and the fraction of cross section occupied by the elements is large, so the mixing efficiency is better than the others, whereas the pressure drop is larger than the others. The new models have been designed to decrease the pressure drop and to minimize the decrease of mixing efficiency as compared with the Sulzer SMX model. The SSC elements have been intended that mixing fluid flowed through 3 mm diameter holes having 27% cross sectional areas per unit element. One set of four SSC elements is aligned as shown in Fig. 3,

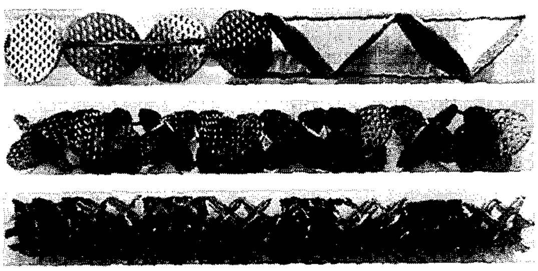
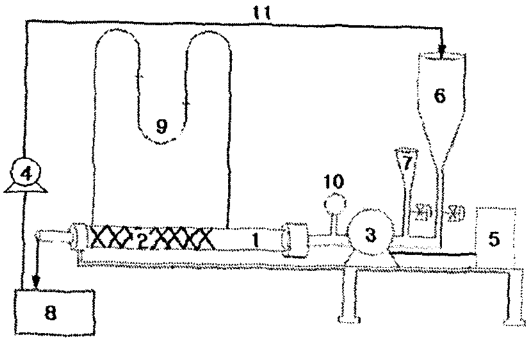


Fig. 3 Three different mixing elements of SSC, YNU and Sulzer SMX type

and the other set is aligned at 90° to the former set. The unit YNU element consists of orthogonally intersecting 2 unit SSC elements (elliptic plates) in Fig. 4. Each unit element of the YNU type is aligned at 90° to its neighbor as the Sulzer SMX. Figure 4 shows the detailed structure of 2 unit elements.

The experimental mixer assembly is shown in Fig. 5. The assembly is a closed loop, consisting of mixing tube, gear pump, 3-phase induction motor, hydraulic manometer and reservoirs. The experimental apparatus has a 40 mm i.d., 50 mm o.d., and 700 mm length acrylic mixing tube which is fitted with 4, 8 or 12 elements respectively in series for three different type mixers. A gear pump (Viking Spur Gear Single Pump; SG-0570) feeds mixing fluid from a fluid head reservoir to the mixing tube. A fluid pump has been used to pump mixing fluid from a lower reservoir to a head reservoir, where a constant level is maintained via an overflow loop from the head reservoir back to the lower reservoir. The gear pump has been driven by a variable-speed 3/4hp 3-phase induction motor. The mixing elements and experimental mixer assembly have been fabricated by a local company in Yeosu; Sin-Sung Ltd.. Table 1 presents the specifications of experimental mixer assembly.

Fig. 4 Geometrical structure of 2 elements of SSC, YNU and Sulzer SMX type



1. Mixing tube
2. Mixing element
3. Gear pump
4. Fluid pump
5. Motor
6. Fluid head reservoir
7. Dye head reservoir
8. Fluid reservoir
9. Hydraulic manometer
10. Pressure gauge
11. Fluid feed line

Fig. 5 Schematic diagram of the experimental motionless mixer assembly

2.2 Experimental method

Pressure drop across the static mixer elements of different designs and numbers has been measured by using a U-type hydraulic manometer. Manometer tapings were provided on the acrylic tube at regular intervals so that pressure drop across different number of elements could be measured. Glycerin (95% pure, Kangnam Industry) has been used as a mixing fluid. The viscosity (μ) and the density (ρ) of the mixing fluid are 1.49 N·s/m^2 and 1257.6 kg/m^3 respectively. The mixing fluid was prepared for experiments by decanting the fresh material from bulk drums to the lower reservoir. The mixing fluid was allowed to settle for at least 2 hours to allow any air bubbles entrained during the decanting process to rise to the surface. The settled mixing fluid was then slowly pumped into the tube to allow all air in the mixer tube to be displaced as the mixing fluid entered. After the mixer tube has been filled, the pump was stopped and the head reservoir was topped off with fresh mixing fluid and allowed re-settling for about 1 hour. Flow rate to the mixing tube has been adjusted through the rpm control of 3-phase induction motor. The scope of this research was limited to testing glycerin at low Reynolds numbers ($Re<20$), which were in laminar regime. All the experiments were carried out systematically with varying operating

Table 1 Specifications of experimental motionless mixer

Diameter of mixing tube	40 mm
Length of mixing tube	700 mm
Length of unit element	40 mm
Element thickness	2 mm
Entrance length of mixing tube	90, 130, 170 mm
Exit length of mixing tube	50 mm

parameters: volume flow rate (7.67×10^{-5} to $2.64\times10^{-4}\,m^3/s$); mixing element type (SSC, YNU and Sulzer SMX); number of mixing elements (4 to 12).

3. Results and Discussions

The pressure drop across a motionless mixer is essential in order to size pump correctly or extruder that feeds the mixer. Excessive pressure drop will result in poor mixer performance excessive energy consumption. Flow restrictions of a mixer require higher operating pressures than actual pressures, resulting in higher energy consumption. The aim of investigation of pressure drop is to find energy loss for different type mixers and to judge the effect of number of the elements. In the literature, the pressure drop correlations are presented in two different ways. First, a Z factor, the ratio of the pressure drop through a motionless mixer to the pressure drop in an empty tube (Hobbs, 1997), has been introduced;

$$Z(Re)=\frac{\Delta p_{sm}}{\Delta p_{et}} \tag{1}$$

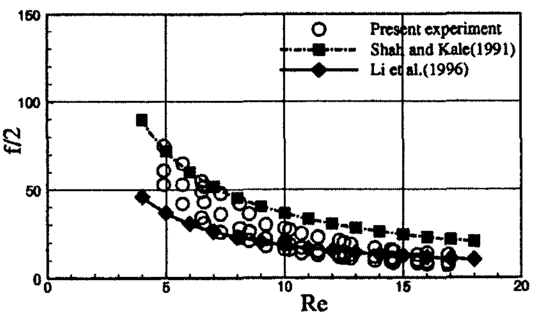
where Δp_{sm} is the pressure drop through the motionless mixer and Δp_{et} is the pressure drop in the empty tube. The other way uses the friction factor f/2 or 4f. That is

$$f/2(Re)=\frac{\Delta p_{sm}D}{\rho v^2 L} \tag{2}$$

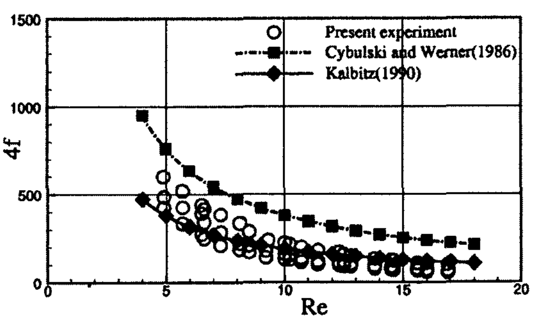
where L is total length of the mixer with multiple elements, D the mixer diameter and Re is defined, $Re=\rho vD/\mu$. Some authors use a void factor ε of the mixer elements to define the generalized Reynolds number, $Re_g=\rho vD/\mu\varepsilon$. In general, the Z factor method for the Kenics type mixers and the friction factor method has been used for Sulzer type mixers as reviewed by Cybulski and Wener (1986) and Rauline et al. (1998). The available experimental data contain significant variability, partially due to slight differences in geometry, different measurement locations, or variations in the method of correlation.

The investigation of pressure drop after passing the motionless mixer element was carried out under the conditions mentioned in the previous chapter. The investigation involved measurements of the following quantities; volume flow rate, density and viscosity of the mixing fluid. These data served for calculation of the friction factor f/2 or 4f and Reynolds number. First of all, in order to assess the accuracy of the experiment, the friction factor results are compared with literature data. Figure 6 shows the comparisons of the friction factors obtained by us with the data published for the Sulzer SMX mixer. The friction factors decrease with the Reynolds number Re. Despite slight differences, the results are qualitatively good agreement with the data by Shah and Kale (1991), Li et al. (1996), Cybulski and Wener (1986) and Kalbitz (1990).

Figure 7 shows the correlations of friction factor of Sulzer SMX, of YNU and of SSC mixers. The correlations (Eqs. (3) ~ (5)) established between the friction factor and Re are good agreement with the correlations for the Sulzer SMX mixer (Li et al., 1996).



(a)



(b)

Fig. 6 Comparisons of the friction factors of Sulzer SMX mixer

Sulzer SMX mixer : $f/2=855\text{Re}^{-1.61}$ (3)

YNU mixer : $f/2=858\text{Re}^{-1.60}$ (4)

SSC mixer : $f/2=344\text{Re}^{-1.42}$ (5)

Figure 8 shows the comparison of average friction factors of 4, 8 and 12 elements with each type mixer. It can be seen that pressure drop across Sulzer SMX and YNU mixers is roughly similar. On the average, the friction factors of SSC and YNU mixers are about 36% lower than and 6% higher than that of the Sulzer SMX, respectively. It can be found that the geometrical configuration of elements seems to have much influence on the parameter. This fact may be attributed to the additional, so-called minor losses due to the relatively complicated geometrical configuration of Sulzer SMX and YNU elements compared to SSC element. It is due to the fact that the skin friction and to some extent the form drag around the mixing elements may contribute more to the increased pressure drop. These additional losses may have characteristics of creeping flow as well as boundary layer flow at low Reynolds numbers (Shah and Kale, 1991).

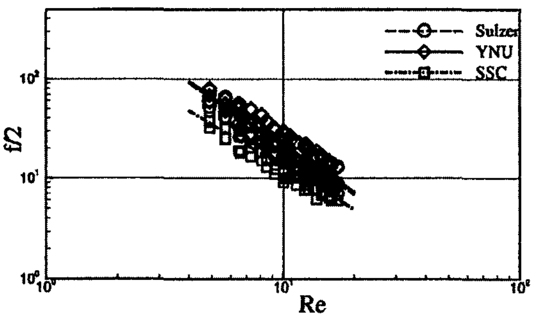


Fig. 7 Correlation of the friction factors of Sulzer SMX, YNU and SSC mixers

Figure 9 shows the comparison of friction factors with the number of motionless mixer element. As expected, the friction factors increase with the number of element. Because of additional obstruction in the path of flow, a greater pressure drop is needed to maintain the same flowrate when more mixer elements are inserted in a tube. Also, it is due to the fact that the smaller the passageways and the larger the fraction of pipe cross section occupied by elements, the higher the pressure drop. As the number of element increase 2 and 3 times, the friction factors of the Sulzer SMX and YNU mixer increase about 0.25 and 0.65 times. On the other hand, the friction factors of SSC one increase about 0.17 and 0.42 times. From the results, it can be seen that as the number of element increase, the increasing rate of the friction factor of Sulzer SMX and YNU mixers is higher than that of SSC mixer.

As a result, in pressure drop (friction factor), that is, energy loss, the SSC mixer is superior to the YNU and Sulzer SMX ones. However, in order to conclude that which one is far superior to, further investigations should be made to quantify the mixing efficiency or homogenization and to investigate the influence of the mixing fluid and the mixer diameter, and it is necessary to consider the hardness and the cost of manufacturing of the element and the problem of cleaning of elements in time of breakdown.

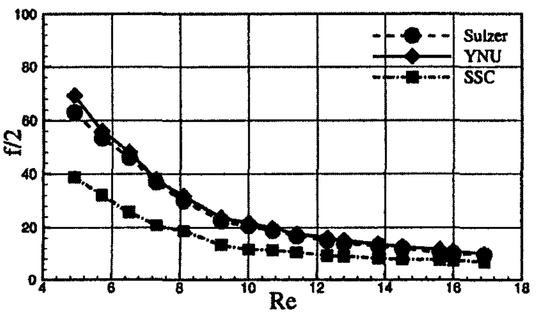


Fig. 8 Comparison of the average friction factors of Sulzer SMX, YNU and SSC mixers

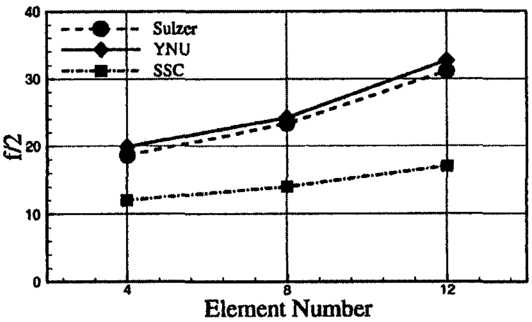


Fig. 9 Comparison of the friction factors with the number of element

4. Conclusions

An experimental study was performed to develop new motionless mixers and to investigate the pressure drop. It can be concluded as followings ;

(1) The friction factors of Sulzer SMX mixer are qualitatively good agreement with the published data.

(2) The friction factors of SSC and YNU mixers are, on the average, about 36% lower than and 6% higher than that of the Sulzer SMX, respectively.

(3) The correlations established between the friction factor and the Reynolds number are in good agreement with the correlations found in literature.

(4) As the number of element increase, the increasing rate of the friction factor of Sulzer SMX and YNU mixers is higher than that of SSC mixer.

(5) For complete comparison, further investigations should be included the mixing efficiency and the influence of the mixing fluid and the mixer diameter, and to consider the hardness and the cost of manufacturing of the mixer.

References

Bauman, I., 2001, "Solid-Solid Mixing with Static Mixers," *Chem. Biochem. Eng.*, Vol. 15, No. 4, pp. 159~165.

Chandra, K. G. and Kale, D. D., 1992, "Pressure Drop for Laminar Flow of Viscoelastic Fluids in Static Mixers," *Chem. Eng. Sci.*, Vol. 47, pp. 2097~2100.

Cybulski, A. and Werner, K., 1986, "Static Mixers-Criteria for Applications and Selection," *Int. Chem. Eng.*, Vol. 26, pp. 171~180.

Hobbs, D. M., 1997, "Characterization of a Kenics Static Mixer Under Laminar Flow Conditions," Ph. D Thesis, The State University of NewJersey.

Jaffer, S. A. and Wood, P. E., 1998, "Quantification of Laminar Mixing in the Kenics Static Mixer : An Experimental Study," *The Canadian J. of Chem. Eng.*, Vol. 76, pp. 516~521.

Kalbitz, H., 1990, "Effect of Static Mixer on the Flow, Heat Transfer and Pressure Drop in Tube Heat Exchanger," Ph. D Thesis of University of Braunschweig (TU), Braunschweig, Germany.

Li, H. Z., Fasol, C. H. and Choplin, L., 1996, "Hydrodynamics and Heat Transfer of Rheologically Complex Fluids in a Sulzer SMX Static Mixer," *Chem. Eng. Sci.*, Vol. 51, No. 10, pp. 1947~1955.

Myers, K. J., Bakker, A. and Ryan, D., 1997, "Avoid Agitation by Selecting Static Mixers," *Chem. Eng. Prog.*, Vol. 93, No. 6, pp. 28~38.

Pahl, M. H. and Muschelknautz, E., 1982, "Static Mixers and Their Application," *Int. Chem. Eng.*, Vol. 22, No. 2, pp. 197~205.

Rauline, D, Tanguy, P. A., Belvec, J. L. and Bousquet, J., 1998, "Numerical Investigation of the Performance of Several Static Mixers," *The Canadian J. of Chem. Eng.*, Vol. 76, pp. 527~535.

Shah, N. F. and Kale, D. D., 1991, "Pressure Drop for Laminar Flow of Non-Newtonian Fluids in Static Mixers," *Chem. Eng. Sci.*, Vol. 46, pp. 2159~2161.

Sir, J. and Lecjaks, Z, 1982, "Pressure Drop and Homogenization Efficiency of a Motionless Mixer," *Chem. Eng. Commun.*, Vol. 16, pp. 325~334.