Motionless Mixers For Viscous Polymers

A fairly recent development in mixing involves the insertion, into a pipe, of shaped elements that divide and swirl the fluid. Without moving parts, and powered only by the pressure drop in the liquid, they provide a neat answer to many problems.

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In polymer processing, the viscous fluids are transported in conduits either between processing units or to distribution systems. It is necessary to maintain uniform quality of the polymers and to keep them from degrading.

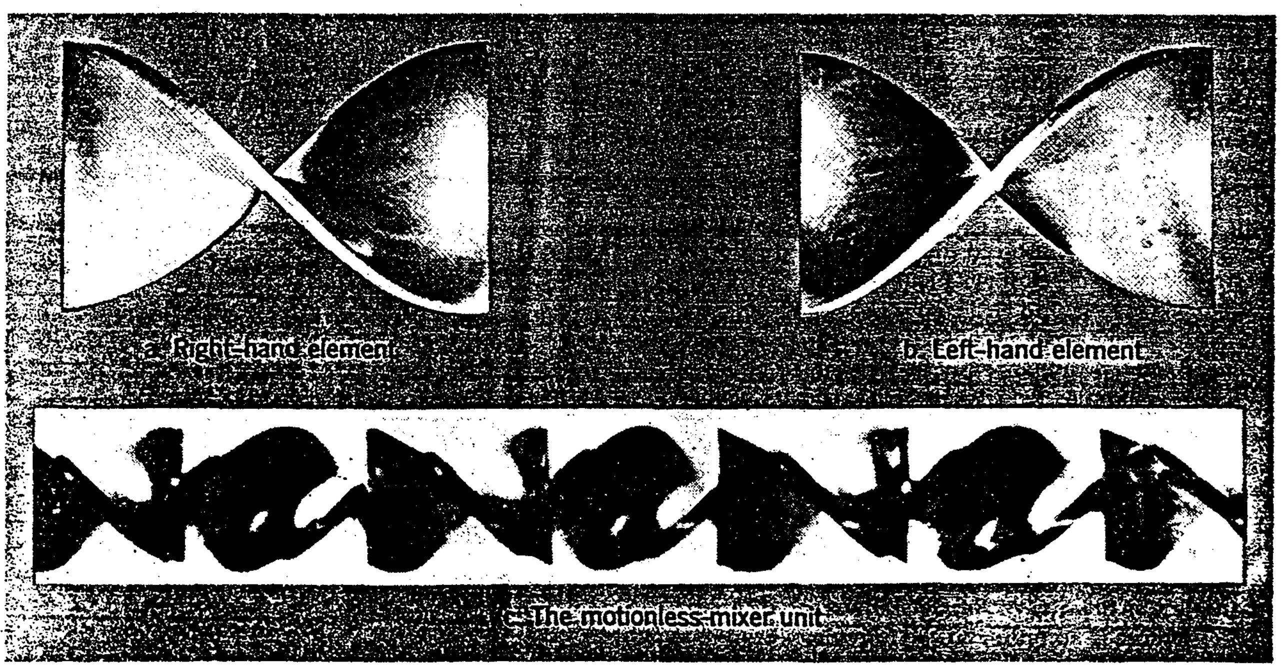
Very often, it is necessary to mix other ingredients intimately into the polymer stream, materials such as antioxidants, flame retardants, colorants, plasticizers, fillers, pigments, and light and heat stabilizers. Mixing additives into polymer streams often involves additive ratios of 1 to 2%, and viscosity ratios of several orders of magnitude between constituents. Achieving a uniform terminal blend under these adverse conditions poses a serious problem to the process engineer.

When cooling or heating of polymers is required, processing is complicated because of their low thermal conductivity. Recently, several inline nondynamic devices for inducing a mixing action in the stream have been investigated, but deficiencies such as plugging, excessive pressure drop, or insufficient mixing have plagued such installations.

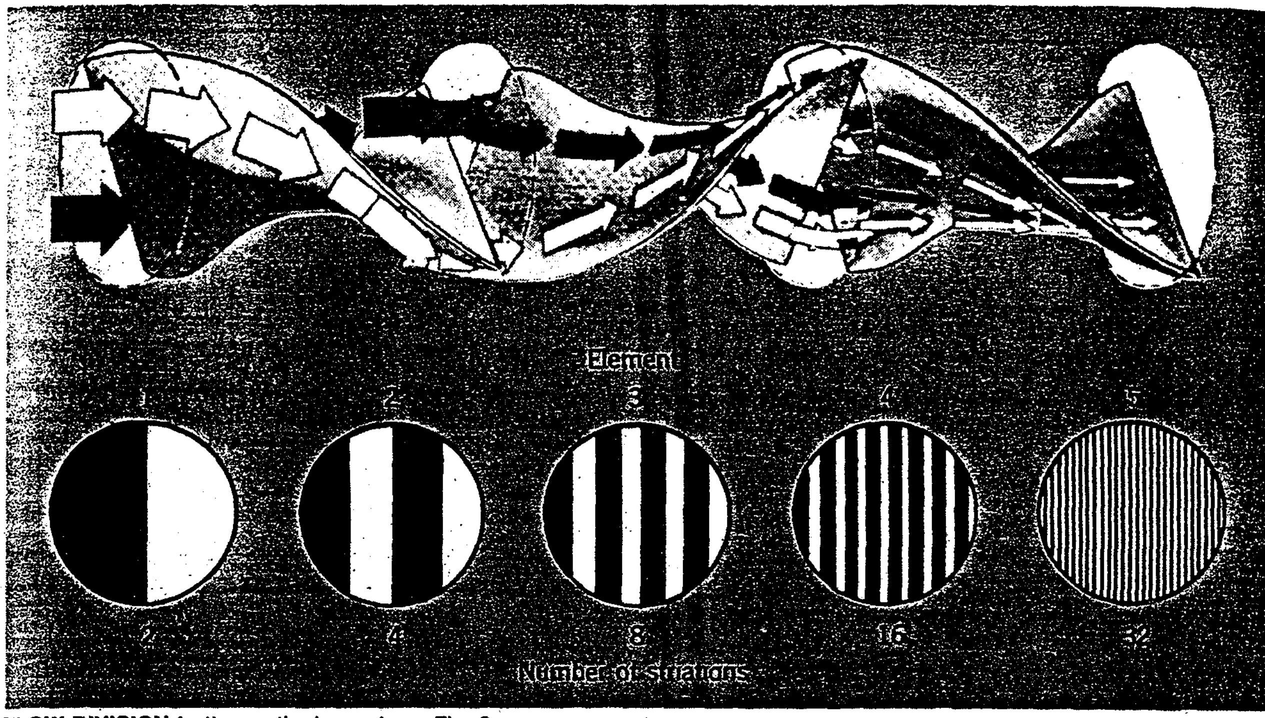
This article deals, in part, with the contribution of a motionless-mixer concept to the mixing and processing of polymers.

Degradation of polymer quality between reactor (or extruder) and ultimate point of use (through the distribution system) is a major concern to the industry. Of several mechanisms of degradation, radial variations in temperature, velocity (and hence the residence-time distributions) of the polymers in the processing system will be examined here. Better heat transfer during processing will also be discussed.

The motionless-mixer concept described contributes in these areas because of its complete radial mixing and its optimal orientation of the flow streamlines in the unit,



MIXER elements and an assembled mixer—Fig. 1



FLOW DIVISION in the motionless mixer—Fig. 2

ensuring that the product formed is a composite that has a uniform molecular weight.

Principles of Operation

The motionless mixer discussed here is a no-moving-part, ductlike mixing device. It uses no external power except for the power loss due to the pressure drop of the fluids that pass through it. It is constructed of a number of short elements, cut from conventional right- and left-hand helixes. These short helical elements are alternated and welded together, oriented such that their leading edges are at 90 deg. to the trailing edge of the one ahead.

In general, the length of the individual segments are approximately 1.5 diameters. Such segments are welded or bonded to form a single-piece insert for placement within the tubes. Fig. 1 shows the right- and left-hand helixes and the assembled mixer.

A wide range of materials can be used to fabricate the unit, such as carbon and stainless steels, alloy and exotic metals, glass-fiber-reinforced plastic, polyvinyl chloride (PVC) and other plastics, glass and ceramics.

When the materials to be mixed are passed through the mixer, two unique mixing actions, flow division and radial mixing, operate simultaneously in the unit, resulting in average plug-flow characteristics. The two mixing actions are flow division and radial mixing.

Flow Division—As the flowing material contacts the leading edge of a helical element, the fluid is split into two and forced to follow the geometric path created by the element shape. At the succeeding element, the two flows are split into two again, thus creating a mathematic progression of division of the flowing stream. The progression proceeds according to the formula:

$$S = 2^n \qquad (1)$$

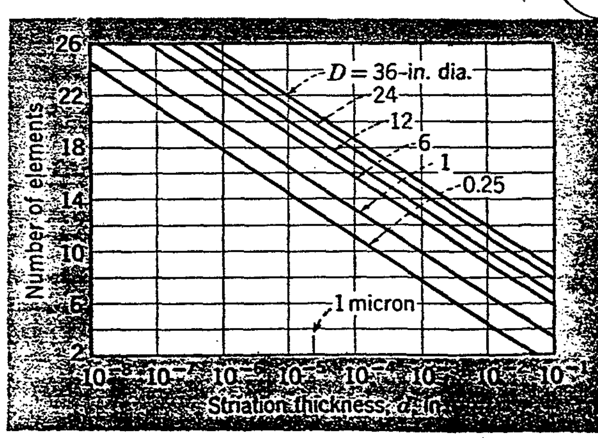
where S is the number of strata produced and n is the number of elements in the unit. Over a million strata are created after 20 elements.

Fig. 2 shows division of flow in the mixer. For laminar flow, the thickness of striation, d, is defined as:

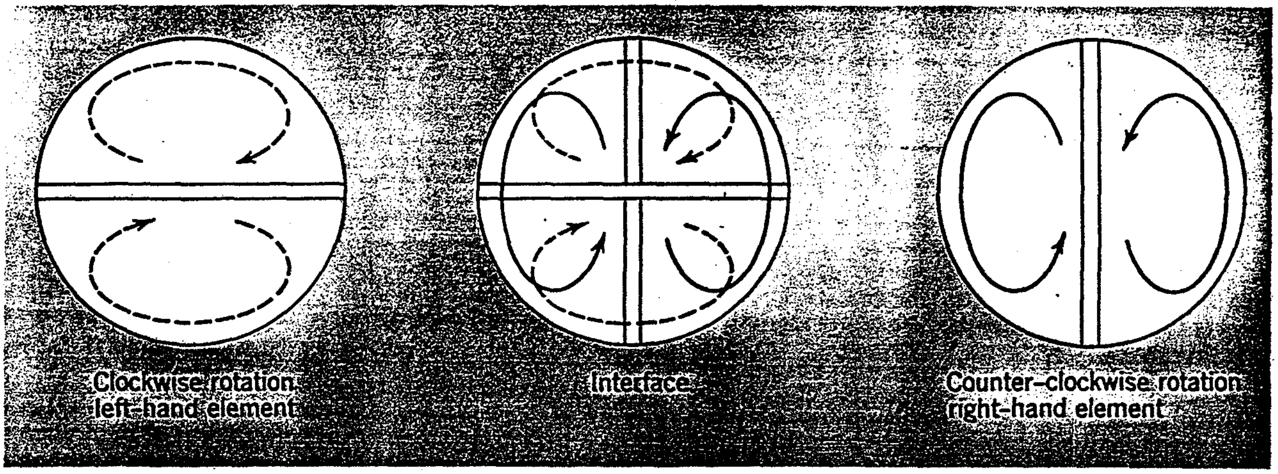
$$d = \frac{D}{2^n} \qquad (2)$$

where D is the inside diameter of the unit. Fig. 3 presents the thickness of striation versus the number of mixer elements, for mixer units of different sizes.

Radial Mixing—In either laminar or turbulent flow, rotational circulation of a processed material around its hydraulic center in each half of the helix region causes radial mixing of the material. The velocity components of the flow in the unit are shifted, creating a new series of velocity vectors and thus forcing the materials from the center outward to the outer wall of the tube.



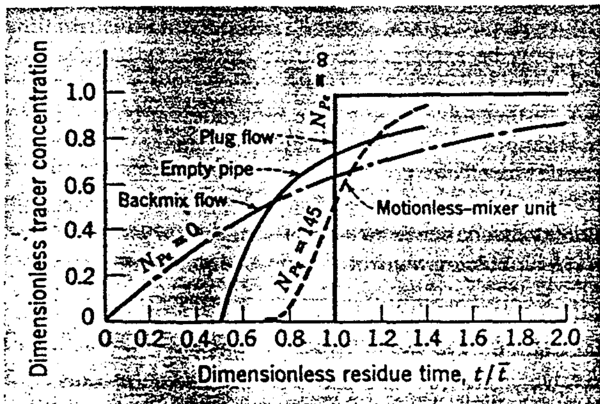
STRIATION thickness vs. number of elements—Fig. 3



RADIAL MIXING mechanisms in the mixer—Fig. 4

Nomenclature

- C — Specific heat of liquid, Btu./(lb.)(°F.)
- D — Inside dia. of unit, in.
- d — Thickness of striations produced in mixer, in.
- E — Axial dispersion coefficient, ft./sec.
- h_i — Inside heat-transfer coefficient, Btu./(hr.)(sq.ft.)(°F.)
- k — Thermal conductivity, Btu./(hr.)(sq.ft.)(°F.)
- L — Length of the mixer, ft.
- L' — Length of the unit in which fluid is undisturbed, in.
- N_{Nu}, $N_{Nu(SM)}$ — Nusselt number of pipe and Nusselt number of motionless mixer of similar dimensions, respectively, dimensionless
- N_{Pe} — Peclet number, dimensionless
- N_{Re} — Reynolds number, dimensionless
- n — Number of helical elements in mixer
- q — Volumetric flowrate, cu. cm./sec.
- S — Number of strata produced
- t — Actual residence time, sec.
- $\bar{t}$ — Mean residence time of fluid in system, sec.
- U — Overall heat-transfer coefficient, Btu./(sq. ft.)(hr.)(°F.)
- V — Effective volume of system, cu. cm.
- v — Average linear velocity in unit, ft./sec.
- θ — Dimensionless residence time, $t/\bar{t}$
- μ — Fluid viscosity, cp.
- ρ — Fluid density, lb./cu.ft.



RESIDENCE-TIME *distribution curves—Fig. 5*

At the same time, flow is made to reverse its rotation at each element junction, due to the alternate right- and left-hand configuration of the helixes. It may be observed that the fluid rotation in a given hand element is opposite to the rotation of said element: for example, in a clockwise rotated element, the half sections of fluid contained within that element are observed to rotate counter-clockwise.

Fig. 4 shows the rotation of flow in each element and at the interface of the two elements. The overall effect of radial mixing is to cause the stream to be continuously and completely inverted radially, such that particles entering at the center of the stream are forced to the outer wall and vice versa, on a continuous basis. Because of thorough radial mixing in the mixer, transverse gradients in temperature, velocity and composition are eliminated. Precise control over inline processing is assured in numerous blending, dispersion and heat-transfer applications.

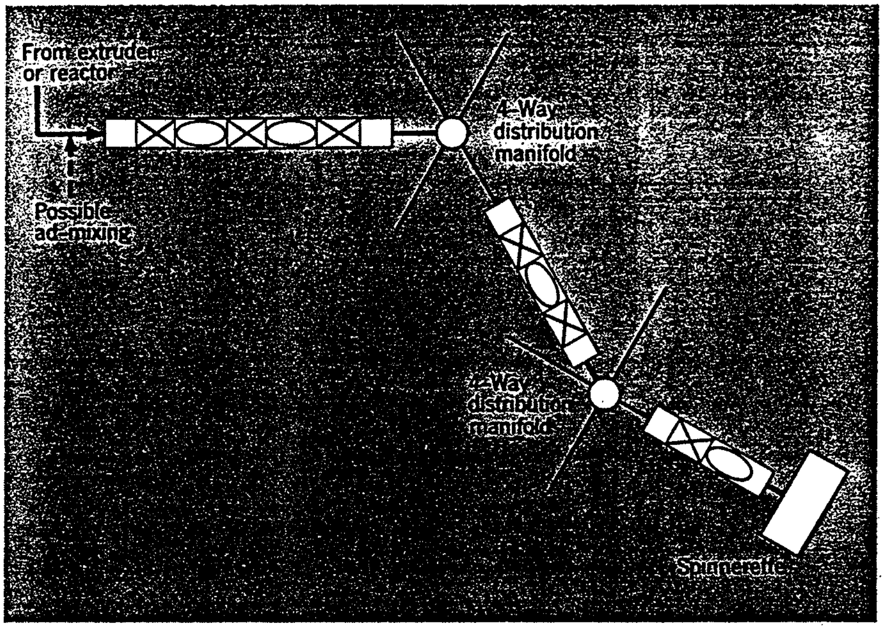
Residence-Time Distribution in Mixer

The techniques of stimulus-response have been widely used to characterize experimental mixing-data in a flow system. In experimentation, we *do something to the* system and then see how it reacts, or responds, to this stimulus. Analyzing the response gives the desired information about the system. The stimulus used in the experiments was the step-input of a tracer to the mixer unit. The response signal was the recording of the concentration of tracer leaving the unit. It was found that characteristics of the mixer approach those of the ideal plug-flow system.

Fig. 5 shows the step-response curves of the mixer tested. Response curves of laminar flow in an empty pipe, and of the ideal plug-flow and complete back-mix flow, are also presented for comparison. The parabolic velocity profile of laminar flow in an empty pipe results in a considerable spread of residence-time distribution.

The response curve of the ideal, complete, backmixing system is an exponential curve, and that for the ideal plug-flow system is a unit-step-function. Mean residence time of the flow system can be defined as:

$$\bar{t} = \frac{V}{q} \qquad (3)$$



MIXERS in typical polymer distribution system—Fig. 6

The dimensionless residence time is defined as follows:

$$\theta = \frac{t}{\bar{t}} \tag{4}$$

For the ideal plug-flow system, all the materials enter and leave at the same time. Therefore, the unit step function starts at $\theta = 1.0$.

If the Peclet number is used to characterize our mixer unit, it is found that for both fluid and solid particles the experimental data are bounded by the Peclet numbers 70 and 220, with the average being 145. The Peclet number is defined as:

$$N_{Pe} = \frac{vL}{E} \tag{5}$$

For the ideal plug-flow system, E is assumed to be zero; thus, the Peclet number is infinity. For the ideal complete backmixing, E is assumed to be infinity; thus, the Peclet number is zero. The response curves for any real flow system lie between these two ideal extreme cases. For all practical purposes, the flow system can be assumed to be plug flow if the Peclet number is greater than 100.[1] By this criterion, the mixer unit tested possesses plug-flow characteristics; one of its most important features. Because of this feature, precise control over inline processing is assured in numerous blending, dispersion and heat-transfer applications.

Temperature rises to its maximum value at the center of the pipe. Small differences in temperature in the cross-section of the pipe are responsible for large differences in the ultimate quality of the product. For example, with certain polymers a temperature difference of 10°C. can account for as much as 100% change in quality of product, as measured by tensile tests of filaments spun from the polymers. This problem is complicated when it is necessary to divide the stream to supply multiple spinnerettes. The stream will not divide uniformly, and product quality will not be equal in the divided streams.

Because of the complete, radial, mixing action, the motionless mixer is of value under these adverse conditions in continuously rehomogenizing the polymer stream, thus avoiding the temperature and, therefore, the intrinsic viscosity changes within the stream's cross-section. It is particularly important to install such a device immediately upstream of any distributing manifold to ensure that the stream is uniform in cross-section and possesses uniform thermal history prior to splitting. An example of such a distribution system is shown in Fig. 6.

Ideally, it would be desirable to use the mixer elements throughout the system, thereby enhancing the residence-time-distribution characteristic of the entire plant. However, limitations of pressure drop in existing plants generally preclude this type of installation. Therefore, it is necessary to accept the poorer alternative of installing the units ahead of each distribution point in such a way that maximum interblending of the radial strata is achieved (commensurate with the capacity of existing extruders or pumps, or both). However, even in such retrofit installations, documented cases of a reduction in total intrinsic-viscosity-drop have been reported.

More-extensive application of these mixing devices might be planned for new process designs. Under such circumstances, greater flexibility is possible due to the absence of the constraints of existing piping and equipment. With the reduction of significance of thermal-history control, new concepts of polymer distribution may now be examined to further reduce residence time and degradation.

A further advantage of the motionless mixer in these installations is in the enhancing of the overall heat-transfer coefficient within the mixing zone. Since the mixer unit is functioning to reduce the effect of the wall film in the polymer stream, it reduces the effect of the inner-film factor in the heat-transfer equipment. Improvements of inner-film coefficient of 300% have been observed.

Installation of a motionless mixer in existing plants is relatively simple since the only requirement, once the design and dimension have been determined, is to remove a section of the transfer piping upstream of each distribution point and install in its place a section of motionless mixer equipped with the proper system-rated housing and jacket for the heating medium.

On most occasions, the entire unit is prepared by the manufacturer for installation by the customer. This includes the elements, and the housing and jacket with appropriate flanges (or prepared for butt welding). Alternatively, the manufacturer can install the mixer elements in existing equipment such as piping, pump blocks, goose necks, spinnerette bodies, etc.

Heat Transfer

Heating or cooling viscous polymers has long been a serious problem because most viscous materials have low thermal conductivity and are difficult to mix intimately. Conventional heating or cooling devices have been plagued by hot or cold spots and by incomplete mixing. Consequently, products of nonuniform quality are obtained. As mentioned previously, the complete radial-mixing action in the motionless mixer greatly enhances the rate of heat transfer and eliminates the transverse gradients in temperature and velocity.

The mixer has been used for both heating and cooling of polymers. Experiments conducted at Tufts University indicated that the inside heat-transfer-coefficient of laminar, viscous flow increased 250 to 300% by using the unit as a heat exchanger. Experimental data were correlated for different viscous materials under different operating conditions. Conservatively, the following equation was obtained for laminar flow ($N_{Re} < 2{,}000$):

$$N_{Nu(SM)} = 2.5\, N_{Nu} \qquad (6)$$

The Nusselt number is defined as:

$$N_{Nu} = (h_i d)/k \qquad (7)$$

For laminar flow in empty pipes under conditions where natural convection is negligible, the following equation has been obtained:[2]

$$\frac{h_i d}{k} = 1.86\left[\left(\frac{Dv\rho}{\mu}\right)\left(\frac{C\mu}{k}\right)\left(\frac{D}{L'}\right)\right]^{1/3} \qquad (8)$$

The first dimensionless group in the parentheses of Eq. (3) is the Reynolds number, N_{Re}, and the second group is the Prandtl number, N_{Pr}.

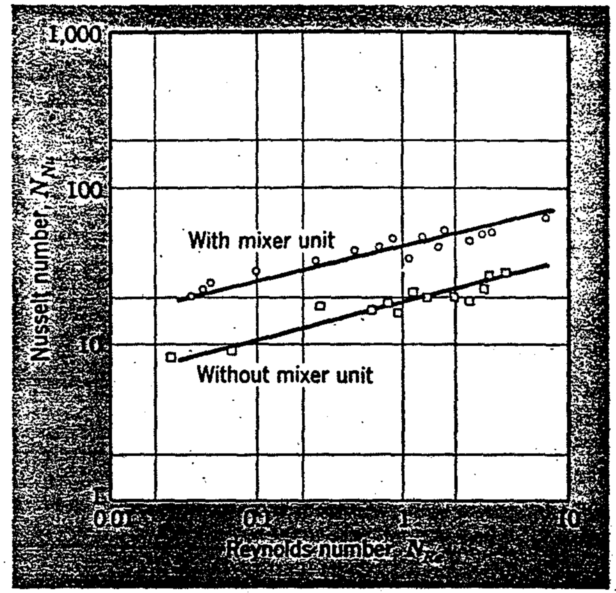
Thus, Eq. (3) can be written as:

$$N_{Nu} = 1.86\,[(N_{Re})(N_{Pr})(D/L')]^{1/3} \qquad (9)$$

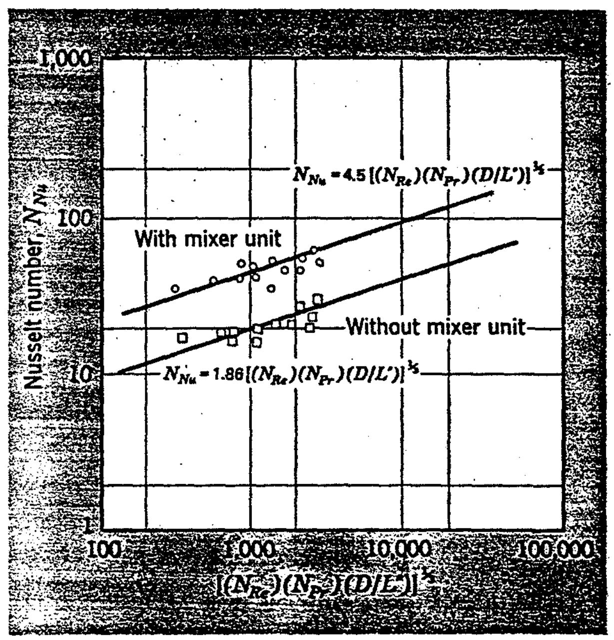
Substituting Eq. (3) into Eq. (1) yields:

$$N_{Nu(SM)} = 4.65\,[(N_{Re})(N_{Pr})(D/L')]^{1/3} \qquad (10)$$

Fig. 7 shows the correlations of the Nusselt number and the Reynolds number. Fig. 8 shows the correlations of the Nusselt number and the product of the Reynolds number, the Prandtl number, and D/L'. In processing viscous polymer melts, the motionless mixer unit has been successfully used in homogenizing melt-temperature gradients generated in an extruder (the unit being installed between the extruder and the die). Thermally homogenized polymer melts with less than 1°F. temperature gradient are delivered to the die. Product uniformity



NUSSELT number vs. the Reynolds number—Fig. 7



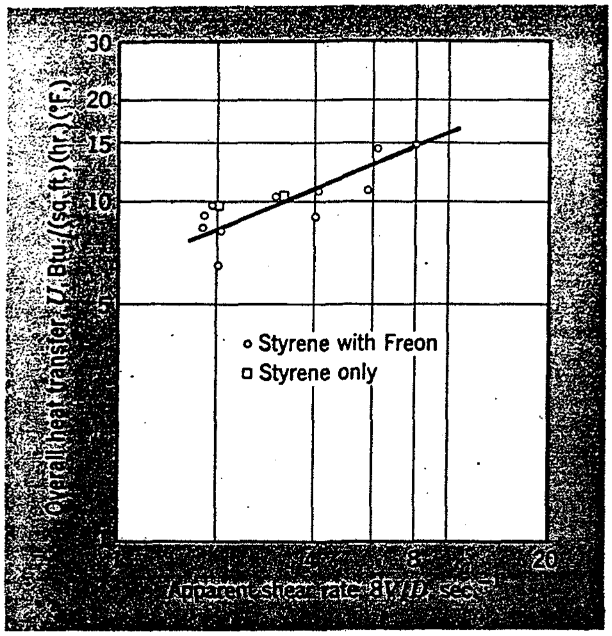
NUSSELT number vs. $[(N_{Re})(N_{Pr})(D/L')]^{1/3}$—Fig. 8

and sheet- and film-gage control have been greatly improved. Improved gage control results in an increase in output and a decrease in product waste.

In cooling viscous polymer melts from an extruder for film-blowing or foaming operations, improved overall-heat-transfer coefficients have been obtained. For cooling highly viscous materials, the inside film resistance is controlling. Therefore, the overall heat-transfer coefficient is approximately equal to the inside heat-transfer coefficient:

$$U \cong h_i \qquad (11)$$

In this case, the overall heat transfer, using the motionless mixer unit, is 250 to 300% higher than that obtained using the conventional heat-transfer device. Fig. 9 presents an



SHEAR rate vs. *U* for melted styrene—Fig. 9

example of the relationship between the overall heat-transfer-coefficient and shear rate. The overall heat-transfer-coefficient increases with the shear rate.

Design and Operation Considerations

Several factors must be considered in designing the motionless mixer unit for admixing in the polymer stream. Of significant importance is the degree of mixedness required for uniform dispersion of additives into the polymer stream. The miscibility, volumetric and viscosity ratios have an effect on the degree of mixedness. In general, a reasonable estimate for uniform blending under continuous laminar-flow conditions is a unit of 18 to 24 mixer elements.

The pressure drop in the unit results from the loss of energy due to friction in the pipe and in the mixer elements (the pressure drop has been found to be a function of the Reynolds number). In processing polymers, the Reynolds number is usually less than 2,000; hence, the flow of polymer melt is in the creeping or laminar-flow region.

If the Reynolds number is less than 10, the pressure drop through the mixer is at most 6 times that of the empty pipe of the same dimensions. If the Reynolds number is between 10 and 2,000, the pressure drop is 6 to 60 times that of the empty pipe of the same dimensions, depending on the size of the mixer unit. The larger the size, the less the pressure drop and the longer the residence time.

In the design and operation of a polymer plant, both the residence time at melt temperature and the pressure drop against which the transfer pumps or extruders must work should be carefully taken into consideration. If it is possible to increase the diameter of the motionless-mixer unit, a reduction in pressure drop will be achieved, but at the expense of residence-time increase. The alternative in control of residence time for a given diameter of the unit is to reduce the number of mixer elements and hence the overall length of the motionless mixer. This, however, will have a detrimental effect on the quality of the mixture. Therefore, the optimal design of the motionless mixer for processing polymers is a function of pressure drop, residence time, and the number of mixer elements needed to achieve the desired degree of mixedness.

In cooling viscous polymer melts, it is not feasible to use a conventional heat exchanger. Another expensive extruder, or other complicated equipment, is used to cool such melts. Cost of the motionless mixer is far less than that of an extruder or other equipment.

Although the significance of thermal-history control is greatest in critical applications such as tire cord, major process gains can be realized in the textile areas as well, in terms of improved dyeability and lot-to-lot uniformity. Applications of the motionless mixer to improve fiber technology have been reported by Riggert[3] and Bor.[4]

Cost effectiveness can be demonstrated in improved product quality (i.e., improved competitive position), virtual elimination of maintenance, low operating cost, and low capital investment when compared to alternatives. Of course, the total lack of moving parts and penetrations such as shaft stuffing-boxes, etc., represents a significant safety factor in reducing the possibility of system leaks. ■

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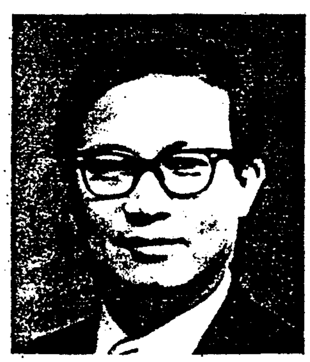

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