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Fiber Melt Extrusion: Deviations from Steady-State Behavior in the Spin Line*

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Synopsis

The occurrence of nonsteady-state conditions in the melt extrusion of fibers is described. Data obtained from cinephotographs are presented which indicate that the spin line diameter at a fixed point in space can have wide fluctuations dependent upon spinning parameters. It is postulated that the interaction of an elastic bulge and variable spin line tension due to a melt inhomogeneity may be responsible for the effect. Some evidence for melt inhomogeneity is presented to demonstrate the existence of domains having flow properties different from the main mass of polymer melt.

Introduction

The mechanical aspects of the formation of fibers from polymer melts are of considerable technological significance, and have undoubtedly received a great deal more attention than the published literature may indicate. However, some of the facets of the process have recently been described. Ziabicki and Kedzierska[1-3] have investigated stream diameter and velocity distribution along the spin line, as well as stream broadening and tensile stresses involved in the process. Andrews[4] has employed an approximate method to solve the heat flow equations involved in the cooling of the spin line. A method for estimating the tension acting on the molten stream by displacing the stream with a controlled airflow is due to Manabe.[5] Thompson[6] has measured optical changes of the stream and derived velocity and birefringence data. The characteristic swelling of a polymer stream which is often observed upon emergence from a tube has been the subject of a detailed study by McIntosh.[7]

The work cited above has been valuable in describing and understanding the nature of what superficially appears to be an inherently simple process; the formation of a fiber of uniform properties by expression of the molten polymer through a capillary. These authors have concerned themselves with steady-state spin line conditions, i.e., those in which the shape of the molten stream is independent of time. In special instances and with certain polymers, however, it is often found that although the volumetric input to the spin line is constant and the fiber is withdrawn from the

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line at a constant linear velocity, mass pulses can be observed to traverse the spin line. It is this nonsteady-state condition with which this paper is concerned. Polypropylene is susceptible to this type of pulsing condition, and we have chosen this polymer to illustrate the effect.

Apparatus and Procedure

The filaments were extruded by use of a screw extruder fitted with a 1-in. diameter 16/1 L/D ratio screw, compression ratio 3.5, which feeds a gear-type metering pump. The molten polymer is metered through a conventional filter pack assembly and extruded through a nine-hole spinneret in which three groups of hole dimensions are available for use: 9 × 12 mil, 15 × 15 mil, and 12 × 18 mil. Any group of three similar sized holes can be selected at will, while the remainder are blocked. The spinneret temperature was 450°F. Shear rates (based upon Newtonian flow) for conditions I, II, and III were 4220, 1690, and 3330 sec.$^{-1}$, respectively. Extrusion was into a stagnant air tube in which drafts were held to be minimal. The polymer was a commercial monofilament grade polypropylene. The takeaway godet is hydraulically driven, and its constancy at various velocities was confirmed stroboscopically.

The spin line was cinemaphotographed by using a Bolex 16 mm. reflex camera fitted with extension tubes so as to give an image two times actual size on the recording film. Photographs were at 16 frames/sec. and the image 2 in. below the spinneret was recorded. The diameter data were obtained by measurement of a 25× enlargement of the image.

Weight per unit length was obtained by actual measurements in sequence along the filament length of filaments obtained during filming.

Results and Discussion

For our purposes we define a steady-state spin line as one exhibiting cylindrical symmetry and whose surface coordinates at any point in space are invariable with time. (By this definition a perfect helix is nonuniform.) Consider the idealized steady-state spin line pictorialized in Figure 1. The polymer melt is extruded at what is known to be a constant volumetric rate through an orifice of diameter D_n, whereupon a swelling occurs to form a bulge of diameter D_b immediately below the orifice exit. The spin line's diameter is attenuated below the region of the bulge solidifying en route and reaching a solidified fiber diameter of D_g and leaves the system at a constant velocity V_g. In this steady-state condition, the continuity equation

$$D\rho/Dt + \rho\,(\nabla \cdot v) = 0$$

applies.

In effect, the process may be thought of as consisting of essentially a two-stage affair, with controlled volumetric delivery of polymer to the bulge and a concurrent withdrawal of polymer from the bulge at a higher

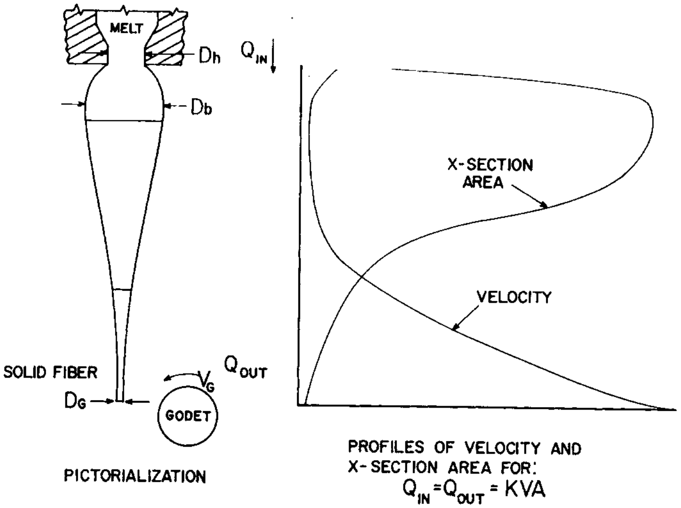


Fig. 1. Idealized steady-state spin line.

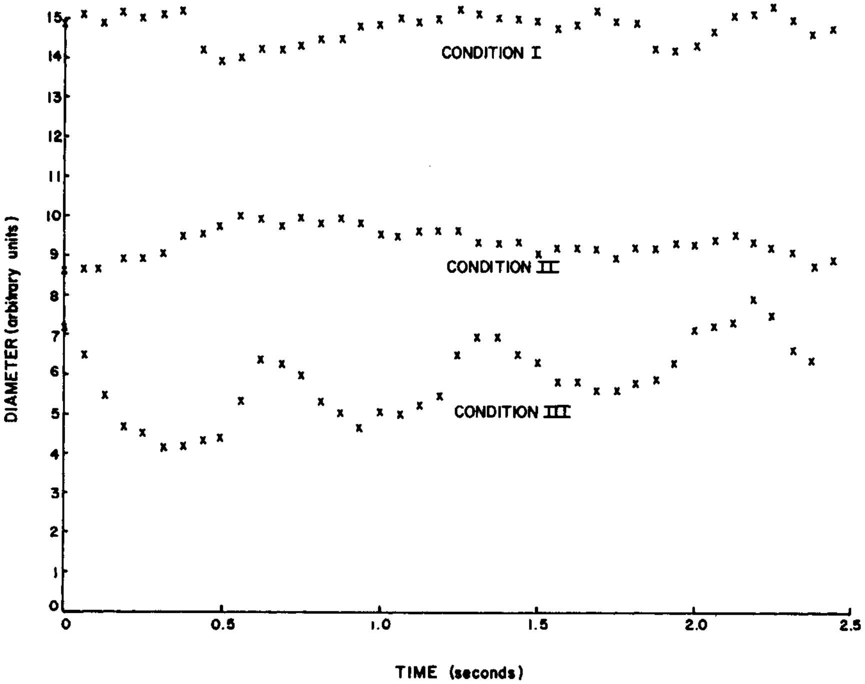
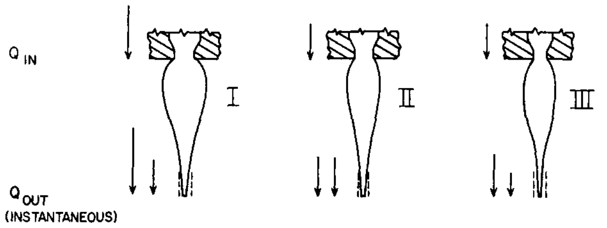


Figure 2.

speed with cooling. When the bulge is capable of undergoing large elastic deformations, serious deviations from steady-state conditions may arise.

To illustrate the nonsteady-state conditions which may prevail there is presented in Figure 2 a plot of stream diameter against time at a fixed point on the spin line, 2 in. below the orifice. Extrusion was at a shear rate of at least 20% lower than that required for the visual onset of melt fracture. The spinning parameters are described in Figure 3. Spin draw is defined for convenience as velocity (Godet)/average velocity (orifice).

The actual weight/length variability of the filaments produced in these sequences are plotted in Figures 4–6. Similar results on a halopolymer appear in Figure 7. The shape of this curve is quite similar to the one obtained by Miller[8] for which he coined the term "draw resonance."



REL. HOLE DIAMETER	1	1	.707
REL. EXTRUSION RATE	2	1	1
REL. GODET SPEED	2	1	1
REL. SPIN-DRAW	1	1	1/2
SPUN DENIER (AVE.)	1	1	1

Figure 3.

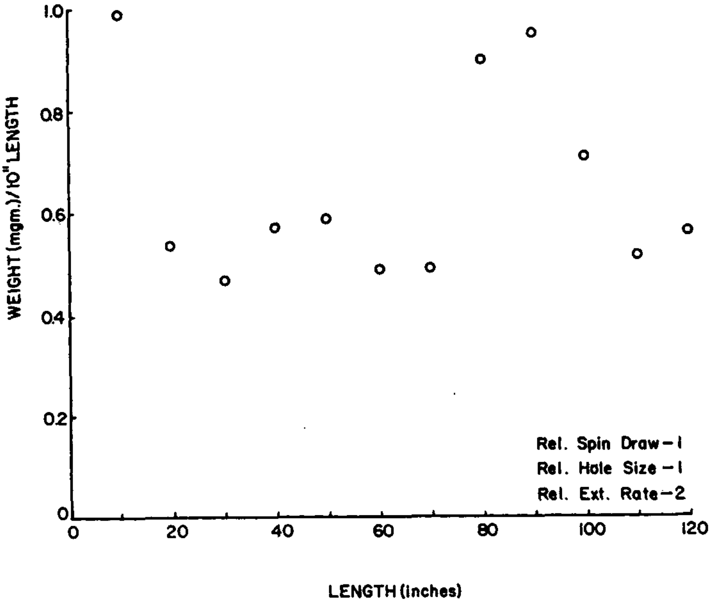


Fig. 4. Polypropylene, spin condition I.

The steady-state spin line condition depicted in Figure 1 obviously does not apply under these conditions. Polymer is being precisely fed into the spin line at a controlled volumetric rate, but the volumetric removal rate

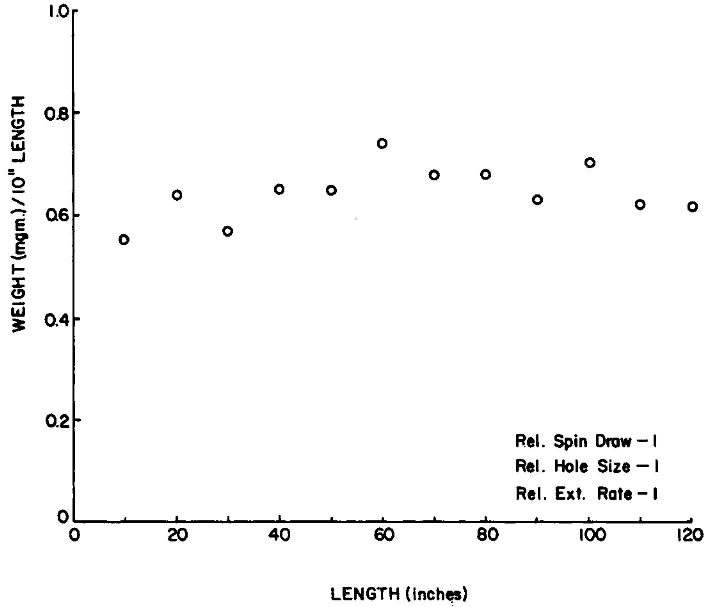


Fig. 5. Polypropylene, spin condition II.

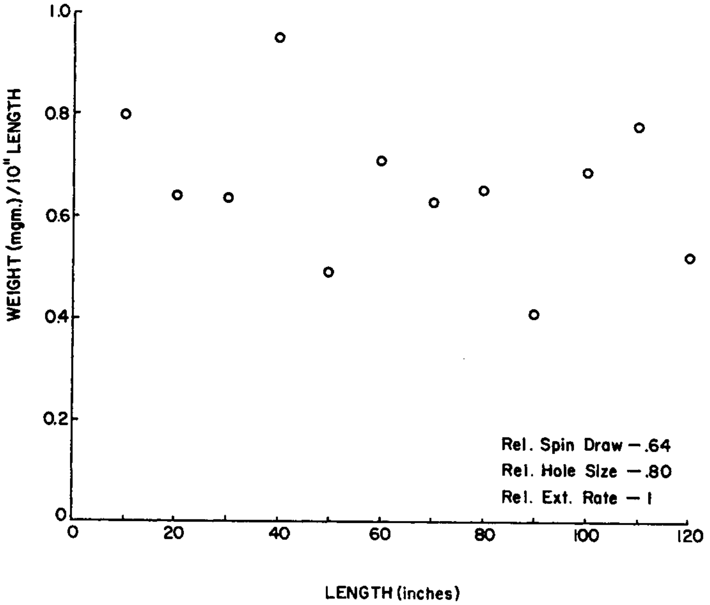


Fig. 6. Polypropylene, spin condition III.

is variable and apparently somewhat periodic in time, a constant linear velocity of removal notwith-standing. The removal godet is known to be moving at constant velocity and with no slippage.

It is possible to consider the steady-state flow condition in the spin line from two approaches. One can confine his attention to a volume element in the spin line between two fixed planes perpendicular to the spin line which are fixed in space. On the other hand, the changing dimension of a volume element can be studied as a function of time and distance along the spin line. In this paper we have chosen to consider the former.

If we examine the conditions requisite for the continuity of flow equation to apply, that is

$$Q = \pi r^2 v$$

(neglecting density changes) where Q is volumetric flow rate, πr^2 is the cross section of the fluid (cylindrical flow) and v is the average velocity at that cross section, it is apparent that the radius must be independent of time at any point in the stream. Otherwise a net local accumulation or discharge of volume must occur. To illustrate with mechanical analogies, Figure 8 depicts a rigid-walled pipe, a distensible-walled pipe, and a pipe whose volume changes sinusoidally with time. If the volumetric input to

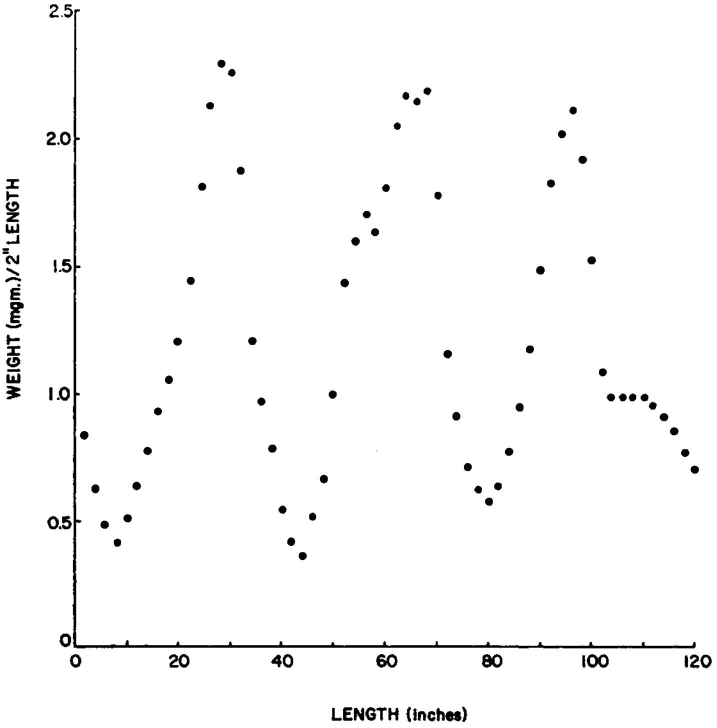


Fig. 7. Halopolymer.

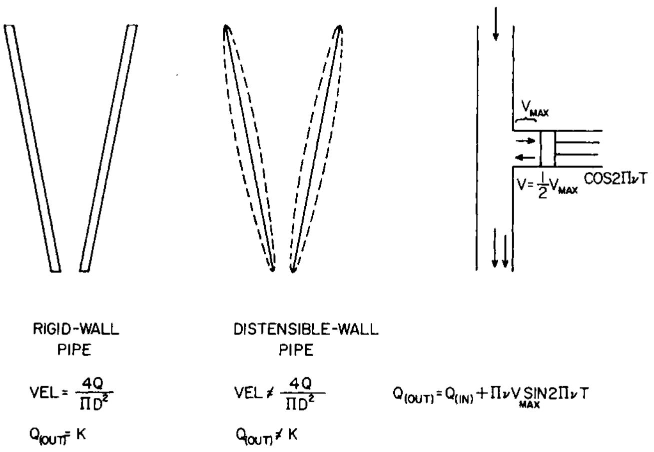


Fig. 8. Idealized model flow schemes.

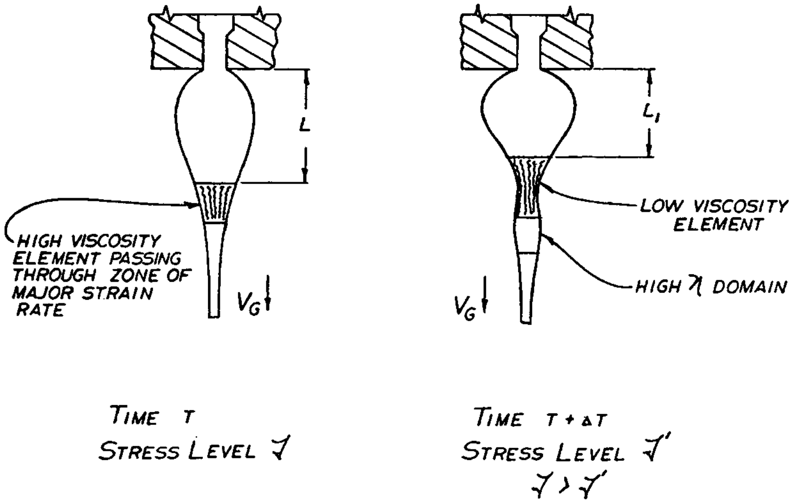


Figure 9.

all three systems is constant, then the output (Q_{out}) of only the rigid wall pipe is constant.

The maximum strain rate $\dot{\epsilon}_{\max}$, in the spin line occurs immediately below the region of the bulge. The strain rates involved in this region are of the order of magnitude of 1–100 × 10^3%/sec.

Consider the effect of having the region of high strain rate coupled in series with a highly elastic element (the bulge) (Fig. 9). The behavior of such a system would be governed in large measure by the elastic properties and dimensions of the bulge and the "micro" viscosity (Trouton) of the melt. (By micro we mean a size order of magnitude corresponding to the

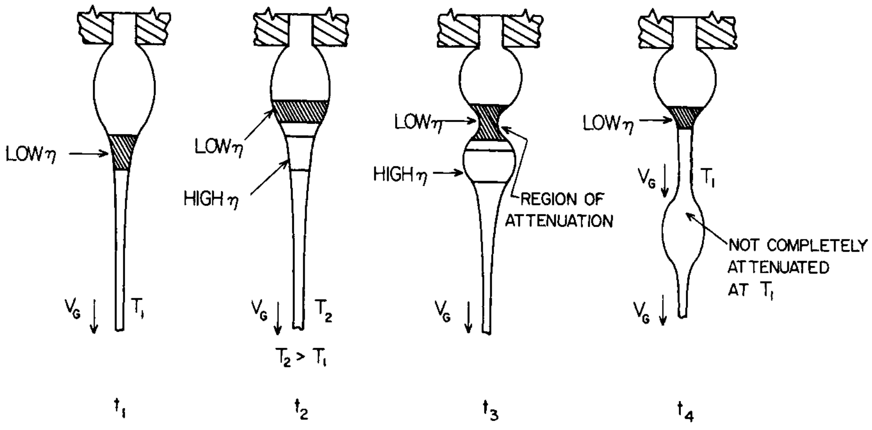


Figure 10.

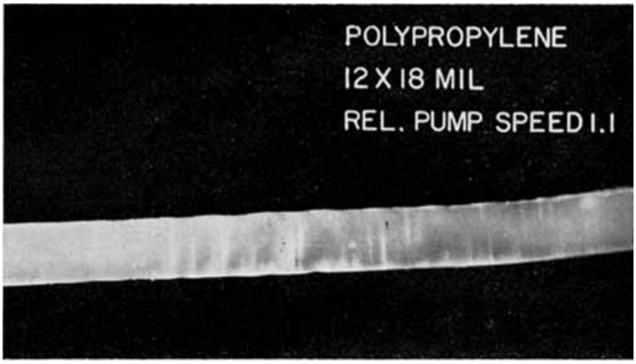


Figure 11.

volume element of the major deformation region.) A nonsteady-state oscillation could arise due to the fluctuation in spin line tension due to melt inhomogeneity and the stored elastic energy of the bulge.

A second type of irregularity which is not dependent on bulge elasticity occurs when the high strain region switches position in the spin line, thereby isolating a small length of spin line. If the region of high strain which contains polymer of a given viscosity receives material of a somewhat higher viscosity, the spinning tension will increase. If, simultaneously, upstream from this point, lower viscosity material enters the line, the higher stress in the line may cause the deformation to occur preferentially in the region occupied by the lower viscosity material even though its cross section may be larger (Fig. 10).

Melt inhomogenity can be due to a variety of causes. Discontinuity of polymer melt flow can be responsible for irregularities in the melt and may be present at a shear rate level which does not lead to visual manifestations of melt fracture such as extrudate roughness, i.e., knots or bumps. Metzger and Brodkey[8] have shown that the true flow curves for polymer melts exhibiting melt fracture do not have a break at a so-called "critical shear stress," but that the curve is smooth, and melt fracture exists over a wide range of shear rates. It should be pointed out, however, that the occurrence of a uniform pattern of melt fracture such as a helix cannot be responsible *per se* for the variation in weight/length along the fiber since such a helix has a constant cross section along its length. If, in fact, the periodicity of the bulge is a manifestation of fracture, it might be of a purely statistical sort arising from polymer melt inhomogeneity. Melt fracture, however, can be a sensitive measure to demonstrate basic inhomogeneity in the melt. For example, Figure 11 shows a section of a filament in which fracture appears over a short length of filament which is uniform over most of its length.

Lack of melt homogeneity in the spin line can arise from incomplete thermal equilibration prior to extrusion, "gel" particles which penetrate the filtration system, shear fractionation, or a domain morphology in the melt.

Melt inhomogeneity is a necessary but not sufficient condition to produce the fluctuating spin line conditions under discussion. In the absence of spin line tension no pulsing is observed. It is only when tension is applied to an apparently steady extrudate stream that the pulsing phenomenon illustrated in Figure 2 makes itself evident.

It is of interest to note that a system operating as described is actually a fractionation device, with high viscosity and low viscosity elements being distributed along the length of the filament. According to this hypothesis the lower viscosity material would be disposed in the troughs and the high viscosity in the peaks. We are presently seeking experimental verification to substantiate this argument.

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Résumé

L'occurence de conditions d'état non-stationnaire dans l'extrusion des fibres à la fusion est décrite. Des données obtenues par cinéphotographie sont présentées et montrent que le diamètre du fil, à un point fixe dans l'espace, peut avoir de larges fluctuations, dépendant de paramètres de filature. Il est postulé que l'interaction d'un branchement élastique et une tension variable de la ligne de filature, due à l'inhomogénéité à la fusion peuvent être responsables pour cet effet. Quelque évidence pour l'inhomogénéité à la fusion est présentée pour démontrer l'existence de domaines, ayant des propriétés d'écoulement différentes de celles de la plus grande partie de la masse du polymère à la fusion.

Zusammenfassung

Das Auftreten von nicht stationären Bedingungen bei der Schmelzextrusion von Fasern wird beschrieben. Aus Filmaufnahmen erhaltene Ergebnisse zeigen, dass der Spinnfadendurchmesser an einem fixen Raumpunkt je nach den Spinnparametern in weiten Grenzen schwanken kann. Es wird angenommen, dass die Wechselwirkung zwischen einer elastischen Ausbauchung und variabler Spinnfadenspannung aufgrund von Schmelzinhomogenitäten für diesen Effekt verantwortlich sein kann. Einige Hinweise über Schmelzinhomogenität werden zum Beweis für die Existenz von Bereichen mit von der Hauptmasse der Polymerschmelze verschiedenen Fliesseigenschaften gegeben.

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