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Stabilization Effects in Flow Through Helically Coiled Pipes

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Abstract. When a flow through a straight pipe is passed through a coiled section, two stabilizing effects come into play. First, in a certain Reynolds number range, the flow that is turbulent in the straight pipe becomes completely laminar in the coiled section. Second, the stabilization effect of the coil persists to a certain degree even after the flow downstream of the coil has been allowed to develop in a long straight section. In this paper, we report briefly on aspects related to these two effects.

1 Introduction

White (1929) – and several others later – made the important observation that the flow in curved pipes can be maintained laminar for substantially higher Reynolds numbers than is possible in straight pipes[1]. Consider now a pipe with a long straight section followed by a helically coiled section. White's observation leads to the logical possibility that, at least in a certain range of Reynolds numbers, the flow that is turbulent in the initial straight section should be capable of being rendered laminar in the coiled section. Figure 1 shows how remarkably complete this process of laminarization can be: a dye streak introduced into the straight section upstream of the coil diffuses rather rapidly, indicating that the flow there is turbulent, while that injected into the fourth coil remains perfectly unruffled for a long distance, indicating the laminar state of the flow there.

The history of studies relating to this interesting phenomenon is very brief, however. After the first recognition by Taylor (1929) that the phenomenon must indeed occur, no attention seems to have been focussed on it until Viswanath et al. (1978) reaffirmed it by setting up a simple dye-injection experiment of the type shown in Fig. 1; see also Narasimha and Sreenivasan (1979). Not much is known about the phenomenon beyond the fact that it occurs; it is this paucity of information that motivated the present study.

The phenomenon of laminarization demonstrated in Fig. 1 naturally leads to several questions. For a given turbulent pipe flow, can one always set up a suitable helical coil which inevitably leads to laminarization? Alternatively, for a given helical coil, what is the maximum flow Reynolds number for which laminarization is possible? What exactly is the role of the tightness of the coil, the number of turns in the coil, etc.? Finally, we were also intrigued by another question: how precisely does the laminarized flow return to a turbulent state when downstream of the coil the flow is allowed to develop in another long straight section?

This paper is devoted to a general discussion of these questions. Obviously, the answer to all these questions is intimately tied down to the critical Reynolds number as a function of position into the coil: if the flow Reynolds number is lower than the minimum Reynolds number at which turbulence can be expected at the given location in the coil, laminarization can be expected to result there. Previously available information (e.g., White 1929, Adler 1934, Itō 1959) on the critical Reynolds numbers in curved pipes has been deduced by measuring a global parameter such as the friction factor; further, most measurements were made in curved sections that were bent to less than one full turn. Such measurements are of limited use for the present purposes, and so, a sizeable part of our effort is

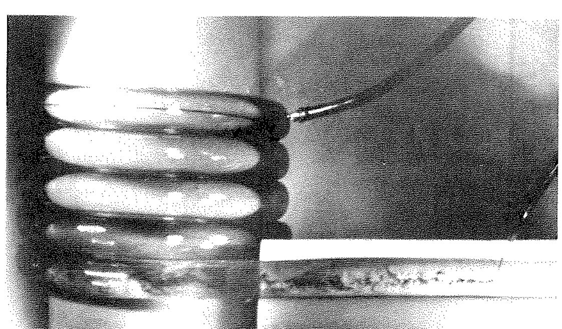

Fig. 1. Laminarization in coiled pipes. Pipe diameter, $2a = 1.91$ cm, radius of curvature, $r = 9.0$ cm, Reynolds number, $R = 4050$

1 Here, we are excluding unusually smooth inlet conditions

related to the measurement of critical Reynolds numbers within the coil.

Anticipating the general nature of our results somewhat, we may comment that the flow under study is characterized by an extraordinary richness of details. We are here limiting ourselves to a rather brief and preliminary description of the phenomenon; a more detailed report must be forthcoming at another time in the future.

2 Experimental Set-up

Figure 2 shows a schematic of the experimental set-up. It consists merely of a certain length of a straight pipe with a standard inlet, followed by a helically coiled section; sufficient development length was allowed for the flow to be fully developed upstream of the coil. The coil itself was followed by another long straight section of the pipe. Several pipe systems were used, but somewhat detailed probing was made in two of them. The details given in Table 1 correspond to the two set-ups, but are typical of the several others also; the chief variation was in the number of coils.

Our initial efforts were with glass tubing but, on subsequent experimentation, we found that even the most carefully bent glass tubes could not maintain a circular cross section to any better accuracy than fairly thick-walled Tygon tubing. For this reason, as well as the ease with which Tygon can be handled, we finally settled on the latter. The worst case for which we have reported the results here corresponded to the ratio of the maximum to the minimum diameter of 1.04. We especially experimented with pipes of varying ellipticity, and discovered

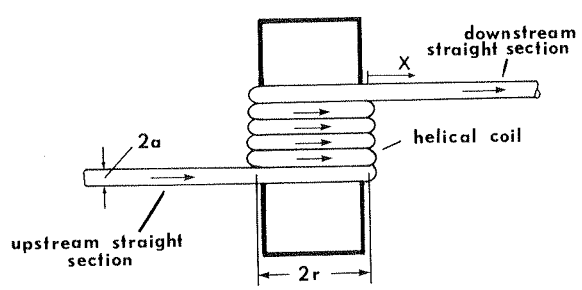

Fig. 2. Schematic of experimental arrangement

Table 1. Some relevant dimensions of two of the pipe systems

Pipe	Inner diameter, 2a (cm)	Radius of curvature, r (cm)	Radius ratio, a/r	$L_1/2a$	No. of turns	$L_2/2a$
I	1.905	16.51	0.058	144[a]	3	162[b]
II	0.635	5.47	0.058	173	20½	937

[a] L_1, Length of straight section upstream of curved section
[b] L_2, Length of straight section following the curved section

that one effect of small departures from circularity was to produce a comparable *lowering* of the critical Reynolds numbers. Thus, we believe that our data on critical Reynolds numbers may perhaps have been *underestimated* by a few percent.

All the data given here were obtained with 5 μm DISA hot wires (length≈0.8 mm) operated at an overheat of 1.75 on a 55M01 DISA constant temperature anemometer. For several corroborative purposes, we made flow visualization studies in pipes with 1.95 cm and 3.18 cm inner diameter.

3 Results

In the straight section upstream of the coil, the lower and upper critical Reynolds numbers – i.e., the highest Reynolds number up to which the flow remains laminar and the lowest Reynolds number at which the flow becomes fully turbulent, respectively – were inferred from hot-wire measurements to be about 2050 and 2800 for pipe I and 2400 and 3300 for pipe II. The differences in these values simply reflect on the differences in inlet conditions. In both cases, transition set in typically by the appearance of turbulent puffs (Wygnanski and Champagne, 1973), and progressed through their coalescence.

In the coiled section, however, the nature of the transition process is much more complex, and some thought is required in the definition as well as the determination of the critical Reynolds numbers. To see this, consider the oscillograms of hot-wire traces shown in Fig. 3. The hot-wire traces correspond to about 0.25 a from the inner and outer walls respectively, both sets taken 2½ coils into the helix of pipe I. Near the outer wall, transition occurs by the formation and coalescence of 'bursts' of high-frequency turbulence. Near the inside wall, on the other hand, the process is completely different: a disturbance at a selected frequency grows to a fairly large amplitude before higher harmonics start to appear (the third trace from the bottom on the left). Soon after, higher and higher frequencies start to appear in a relatively short span of Reynolds numbers.

The differences between transition near the inner and outer walls in the coil are clearly apparent even at half a turn into the coil – which is the smallest distance into the coil that we examined here – and become more and more pronounced until about 3 turns or so. No significant developments occur beyond this, suggesting that some sort of an asymptotic state is reached by the end of about three turns.

A few words are now in order about the frequency of the periodic signals observed near the inside wall. We know of no prototype instability mechanism operating here that explains this feature correctly, although (by accident) the observed frequencies agree closely with that of the most unstable mode calculated in the small-gap limit of

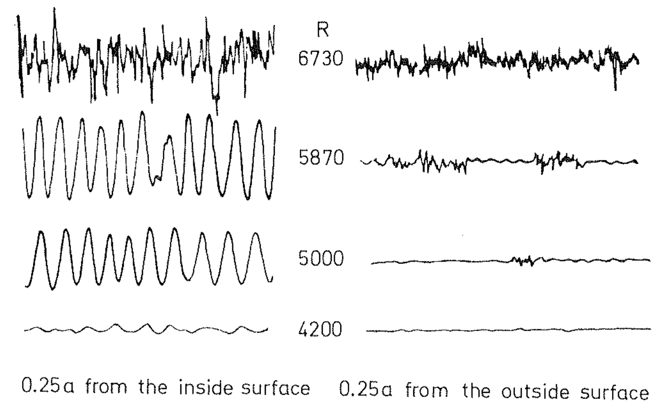

Fig. 3. Typical oscillograms of hot-wire traces during transition in pipe I, 2½ turns into the coil. The corresponding Reynolds numbers are marked in the figure

the Taylor-Couette problem. Our measurements are not extensive at the time of this writing, and merely indicate the occurrence of an intermediate unsteady laminar state of the flow.

The large differences observed in the nature of transition near the inner and outer walls, respectively, suggest that it may be necessary to adopt different techniques for determining the upper and lower critical Reynolds numbers at different locations, typified especially by the said locations near the inner and outer walls. The upper critical Reynolds number near the outer wall can be determined more or less by the conventional method of intermittency measurement. Such methods are of no direct use near the inner wall, however, because turbulence sets in by a continuous infusion of increasingly wider frequency bands. Therefore, we approach the problem of determining the upper critical Reynolds numbers near the inner wall by measuring the spectral density of the streamwise velocity fluctuation, and determining the Reynolds number at which the spectral peak corresponding to the amplified periodic disturbance more or less disappears, and no further change in the spectral *shape* could be seen; clearly, this requires a certain degree of judgment. However, the upper critical Reynolds numbers determined by either of these two ways are the same to within experimental uncertainty, suggesting that the flow becomes fully turbulent at the same Reynolds number everywhere at a given streamwise location. Although this fact lends some confidence to the numbers determined by either method, we should remark here that our confidence in the upper critical Reynolds number is not as high as we would like it to be.

A conservative estimate of the lower critical Reynolds number can be identified with the appearance of the first 'burst' near the outer wall; below this, the flow is laminar everywhere at the specified cross section of the pipe. However, since *most* of the flow, especially towards the inner wall, remains non-turbulent until a much higher Reynolds number is reached, it appears that to identify lower critical Reynolds number uniquely with the first appearance of the bursts is perhaps too restrictive. To reflect this fact in some overall manner, we have also defined a liberal estimate for the lower critical Reynolds number to correspond to the *first* appearance of turbulence *everywhere* at the chosen cross section. In practice, we identify this latter quantity with the first appearance of the second harmonic near the inner wall, the justification being the empirically observed fact that the breakdown to turbulence of the flow there quickly follows the onset of this second harmonic.

For both pipes I and II, the three critical Reynolds numbers determined in the manner discussed above have been plotted in Fig. 4 as a function of streamwise position in the coils. The data are normalized by the lower critical Reynolds number R_o at the entrance to the curved section. The figure shows that the two sets of data collapse rather well. It appears that the flow somehow remembers the initial critical Reynolds numbers (recall that R_o was different for the two pipes) in the straight section, as well as the number of turns it has gone through into the helical coil. All critical Reynolds numbers increase as the flow moves through the coil, with the upper two curves showing steeper rise. It is clear that the total extent of transition – i.e., the distance between the lowermost and the uppermost curves – increases with distance into the coil until about three or so turns beyond which it remains constant. It is also clear that the second harmonic in velocity signals near the inner wall appears closer to the completion of transition than to the onset of bursts near the outer wall.

It is now easy to see that the maximum flow Reynolds number for which complete laminarization is possible corresponds to the conservative lower critical Reynolds number. In the Reynolds number range bounded by the uppermost and lowermost curves such as shown in Fig. 4, only partial laminarization is observable, while no such effect may be expected for Reynolds numbers above the

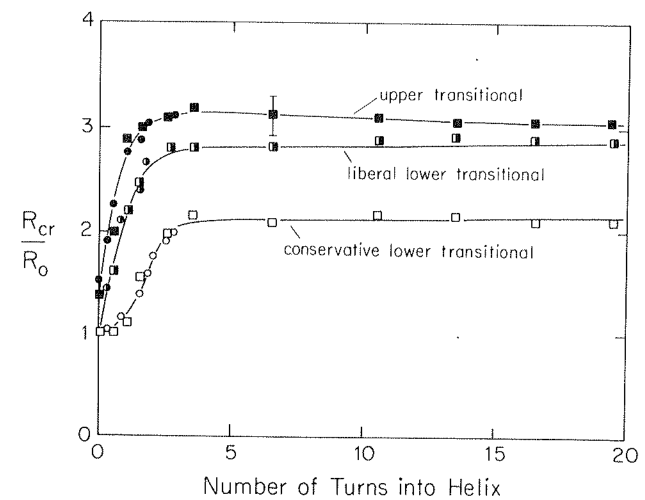

Fig. 4. Critical Reynolds number R_{cr} normalized by the lower critical Reynolds number R_o just before entering the coil. Radius ratio = 0.058. Circles, pipe I; Squares, pipe II

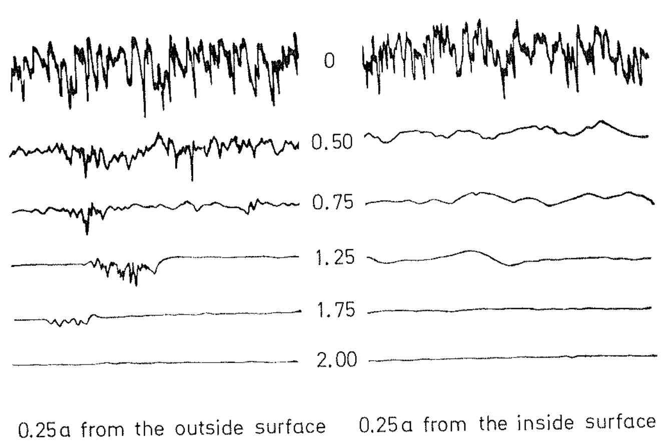

Fig. 5. Typical oscillograms of hot-wire traces during laminarization. $R=3450$, radius ratio $=0.058$, pipe I. The corresponding number of turns into the coil are marked alongside the traces

upper curve. Figure 5 shows oscilloscope traces for a flow undergoing complete laminarization by the end of about two turns into the coil. It is seen that near the inner wall, flow loses most traces of turbulence only half a turn into the coil.

The data of Fig. 4 correspond to a radius ratio (i.e., the ratio of the radius of the pipe to the radius of curvature of the coil) of 0.058. For this radius ratio, a flow with a Reynolds number R can be laminarized completely if $R \lesssim 2\,R_0$ and partially if $R \lesssim 3\,R_0$. An important question is whether these limits can be increased indefinitely by increasing the radius ratio. To that end, we experimented with several coils of varying radius ratios – this variation was obtained in the present experiments solely by tightening the coil more and more, keeping the pipe diameter fixed – and determined the asymptotic values of the three critical Reynolds numbers (Fig. 4). Figure 6 shows the

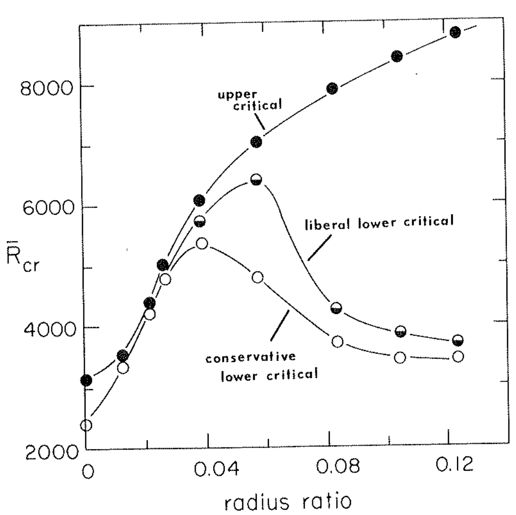

Fig. 6. Asymptotic values of the critical Reynolds numbers $\bar{R}_{cr}$ in the curved section, measured at the end of 20 coils for all radius ratios. Pipe diameter $=6.35$ mm

data. While the upper critical Reynolds number is seen to increase monotonically – at least up to the radius ratio of about 0.12, beyond which the pipe cross section within the coil deviates significantly from circularity – the two estimates of the lower critical Reynolds number reach their respective maximum values and drop! It is clear that complete laminarization is possible only for flow Reynolds numbers below 5200 (corresponding to a radius ratio of about 0.039), and can be partially laminarized for increasingly higher Reynolds numbers by increasing the radius ratio (at least within the range we have examined). Notice the extended gap between the onset and the completion of transition for coiled pipes with radius ratios of the order of 0.1. An explanation for the non-monotonic behavior of the lower critical Reynolds numbers is urgently needed.

We now turn to a brief discussion of the flow in the straight section downstream of the coil; several features of this development are shown in Fig. 7. All the critical Reynolds numbers drop with distance within about the first 100 diameters; however, the critical Reynolds numbers do not asymptote to values appropriate to the straight section upstream of the coil, but stay substantially higher (≈ 5200) no matter how far downstream one measures! (We have measured the critical Reynolds number up to 937 diameters downstream of the coil, but shown the data only up to about 300 diameters.) Further, the distance between the lower and upper critical Reynolds numbers is negligible (only about 0.5% of the lower critical value). Lastly, we may remark that transition here is marked by the appearance of slugs (e.g. Pantulu 1962; Lindgren 1969, also a series of articles in Arkiv Fysik between 1954 and 1963; Wygnanski and Champagne 1973) in contrast to puffs upstream of the coil: slugs are regions of turbulence filling the entire pipe section comparable in length to the pipe length itself, characterized by sharp transitions to turbulence both at the front and the back.

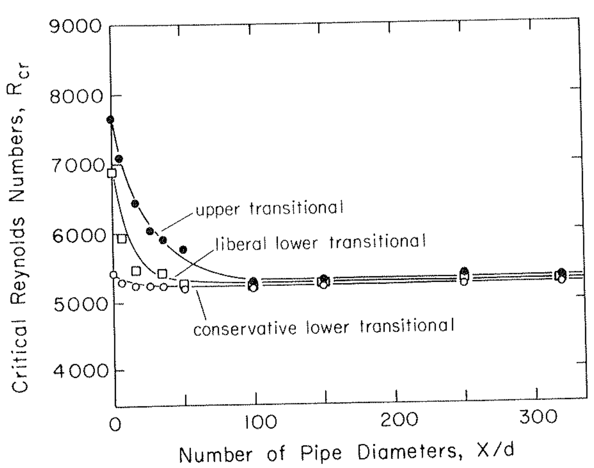

Fig. 7. Critical Reynolds numbers in the downstream straight section, for pipe II

It is of interest to determine the downstream straight section asymptotic Reynolds numbers (compare Fig. 7 for radius ratio of 0.058) as a function of the radius ratio. Since the difference between the lower and upper critical Reynolds numbers is small, we present these data in Fig. 8 as a single Reynolds number. The data closely follow the asymptotic lower critical Reynolds numbers in the coiled section (Fig. 6), and are only fractionally smaller in magnitude.

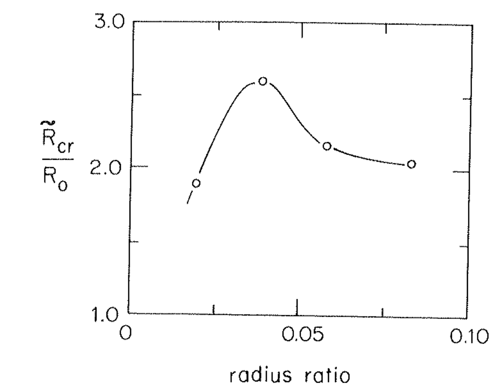

Fig. 8. Asymptotic values of the critical Reynolds numbers $\tilde{R}_{cr}$ in the downstream straight section, measured about 780 diameters downstream of the coil for all radius ratios. Data normalized by R_0. Pipe diameter $=6.35$ mm

4 Discussion and Closure

Some explanation for the stabilizing effects of the coiled section is obviously called for. It is known that the convex curvature (associated with the inside wall) inhibits turbulence, but this explanation cannot clearly be complete because the concave curvature associated with the outer wall is known to promote turbulence. The clues for the somewhat subtle explanation of the phenomenon can be found in Lighthill (1970) and were elaborated upon by Narasimha and Sreenivasan (1979); see also Viswanath et al. (1978). Essentially, in the curved section, the peak of the velocity profile moves to the outside; typically for a radius ratio of 0.058, the peak occurs at a distance from the outer wall of a tenth of the pipe diameter. Over the bulk of the profile from the inside to this peak, the sense of the mean flow vorticity is the same as that of the 'angular velocity' in the pipe, so that, by Rayleigh's criterion – for a statement of the criterion most appropriate in this context, see Coles (1965) – the flow is stable. There is, however, a small region near the outer wall where the mean vorticity and the 'angular velocity' are oppositely aligned. But this region is quite thin for fairly large curvatures, and the governing instability here is of the boundary layer type. This 'boundary layer' too will be stable unless the Reynolds number based on its thickness exceeds a critical value; then and only then will the onset of instability and further transition to turbulence occur. This global stabilization is also the explanation for the occurrence of laminarization, perhaps after the process of 'destruction' of turbulence described by Narasimha & Sreenivasan (1979).

Finally, we may remark briefly on the fact that the flow in the downstream straight section remains laminar for Reynolds numbers higher than the inlet critical Reynolds numbers (see Fig. 8). This seemed surprising at first, but is natural upon recollection that the critical Reynolds number for a pipe flow (i.e., Poiseuille flow), as determined theoretically for *linear* disturbances is strictly infinity. In practice, the pipe flow undergoes transition at finite but variable Reynolds numbers either because the disturbances are not infinitesimal, or the perturbations not axisymmetric or because the boundary layer in the developing region undergoes instability and transition; the actual spectral content of the disturbance is also important in determining the critical Reynolds number. It is possible that the curved section somehow acts as a filter that removes the most critical disturbances, or at least diminishes their amplitude, alter the frequency or both, in such a way that the remainder of the disturbances does not become unstable until after a fairly high value of Reynolds number is attained. The picture is made more complicated by the fact that the return of the mean velocity distribution to an axisymmetric form in the downstream section is slow, and is probably characterized by non-monotonic behavior.

In this paper, we have only briefly touched upon some aspects of the flow and not at all on several related aspects. The most obvious gap in our discussion relates to the absence of mean velocity data both inside and downstream of the coil. Although we have indeed made such velocity measurements in pipe I, they are not sufficiently comprehensive and accurate (chiefly because of the three-dimensional velocity field) to merit presentation. Another aspect we have briefly examined relates to the effect due to a second coil downstream of the first, wound in the same or opposite direction as the first, on the critical Reynolds numbers $\tilde{R}_{cr}$ (Fig. 8), but the details are too complex and are best postponed to a later date.

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