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The effect of a transition curve on the loss of head at a bend in a pipeline†

by

Wilfred Eastwood, B.Eng., Ph.D., A.M.I.C.E.

and

Edward James Sarginson, M.Eng., A.M.I.C.E.

Discussion

Dr Arthur Brebner (Associate Professor of Civil Engineering, Queen's University, Kingston, Ontario) referred to § 6 in which it was stated that "It is unlikely that much of this kinetic energy is converted back into pressure energy after the water leaves the bend". Tests made recently (at Dr Brebner's suggestion) by Mr R. H. B. Hebbert at Queen's University for Aluminium Laboratories Ltd threw further light on that statement.

47. The tests were carried out on a 90° smooth aluminium bend of 6-in. nominal diameter bent to an R/d of 1·5. This bend was preceded by an upstream length of 82 diameters of smooth pipe, for which the variation of friction factor with Reynolds number sensibly followed the smooth-pipe law up to a value of $\frac{vm}{\nu}$ of 5×10^5. (In §§ 24 and 28 of the Paper, ν in this expression was wrongly printed as v.) The downstream tangent was approximately 30 diameters in length and consisted either of smooth pipe or pipe roughened artificially by sand grains of uniform size after Nikuradse[10]. Pressures were recorded at close regular intervals on the downstream tangent by the piezometric orifices of a minute Pitot tube placed at $d/4$ in from the pipe wall, this position being selected because it was believed that secondary currents would affect the mean direction of flow the least at this point.

48. For a smooth downstream tangent the variation in hydraulic grade line with centre-line distance downstream was as shown diagrammatically in Fig. 11. The

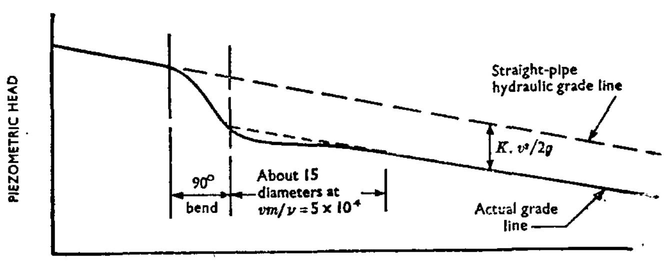

FIG. 11

† Proc. Instn civ. Engrs, vol. 16, pp. 129–142 (June 1960).

regain of kinetic energy was admittedly small but was still noticeable if the piezometric pressure intensity values were to be credited in the spiral motion which was set up in the bend and which persisted downstream. Uniform conditions in that instance were re-established in a much shorter distance than that experienced by the Authors. The "corner" flow found in rectangular pipes was partially the cause of that difference. However, the distance to establish a uniform slope of hydraulic grade line did increase with increasing values of Reynolds number. Also, with increasing Reynolds number the bend loss coefficient was found to decrease, a typical value for that particular bend, when followed by a smooth downstream pipe, being 0·11 at a Reynolds number of 10^5. Such a figure for K corresponded closely to the Authors' value. (A value suggested by Dr Brebner[13] for a 4-in.-dia. welded aluminium 90° bend at $R/d=1$ was 0·28 under normal operating conditions.)

49. With a roughened downstream tangent (but with the same smooth upstream tangent and bend retained) the value of the coefficient tended to be more constant and increased with increasing roughness. The variation in coefficient was as shown in Fig. 12. In those tests the regain of kinetic head was negligible. Fig. 12 showed that

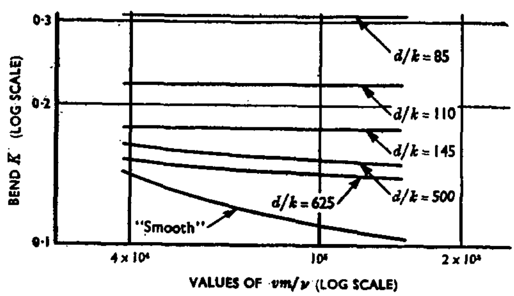

FIG. 12

with increasing roughness an increasing percentage of the bend loss attributed to the bend in reality occurred in the downstream tangent. Such a result was in accordance with the Authors' intuitive statement in § 30 that "the additional loss in the bend could be a function of pipe roughness". The increased loss was readily explicable if consideration was given to the Authors' point that the faster-moving water in the centre of the pipe was moved to the rough outside, and therefore experienced more loss than it would have done under uniform-flow conditions with a stable velocity profile.

50. The head loss could be split into two components, the actual bend loss, $K_a \frac{v^2}{2g}$, and the loss in the downstream tangent, $K_b \frac{v^2}{2g}$. Thus, $K=K_a+K_b$. At a given value of Reynolds number, K_a was constant and K_b was a function of the relative roughness d/k and hence of the friction factor (assuming fully developed turbulent flow it was independent of Reynolds number). The plot of K against f was shown in Fig. 13 and would indicate why previously published results of bend losses for commercial pipes were higher than those obtained by the Authors. The bend roughness itself apparently contributed to the value of K_a, but undoubtedly the major part of the loss attributed to the bend occurred in the downstream tangent, and for Perspex pipe which had an f-versus-Reynolds-number plot similar to that of smooth pipe[14] that loss was a minimum. There was, therefore, a double benefit to be gained in using a hydraulically smooth material for a pipeline containing many directional changes.

[13] The references are listed on p. 205.

51. With regard to nomenclature, Dr Brebner wondered whether it was not preferable to define Reynolds number as:

$$\frac{\text{mean velocity } (v) \times \text{diameter } (d)}{\text{kinematic viscosity } (\nu)}$$

or:

$$\frac{4 \times \text{mean velocity } (v) \times \text{hydraulic mean depth } (m)}{\text{kinematic viscosity } (\nu)}$$

instead of by $\frac{vm}{\nu}$. It appeared to him that the majority of engineers in the field of hydraulics were more familiar with the $\frac{vd}{\nu}$ relation. The Authors themselves were slightly confused by that since, in § 24, they stated that the critical value of Reynolds number $\frac{vd}{\nu}$ was 575 for cylindrical pipes, whereas the value should be 4 times that by the $\frac{vd}{\nu}$ definition.

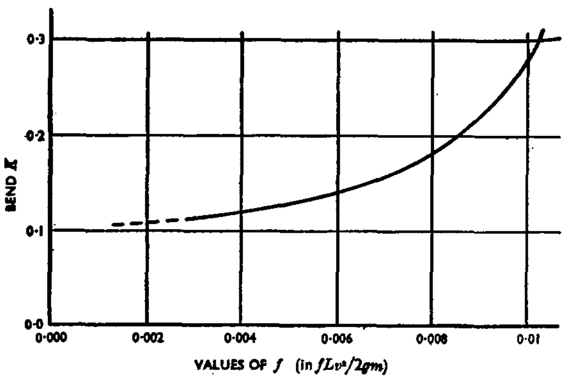

FIG. 13

Dr John Allen (Lecturer in Civil Engineering, Queen Mary College, University of London) said that the Paper was particularly valuable because the Authors had obtained the losses for bends with various arrangements of transition curves.

53. It appeared that many investigators in the past had neglected the effects of transition lengths on the resultant losses of the piping system. That seemed to be a fundamental omission, because the rate of change of the velocity distribution at entry and exit must have a considerable bearing on the efficiency of the bend.

54. If that argument was correct, it followed that the rate of change of curvature could be as important as the actual curvature and cross-sectional dimensions of the conduit.

55. It would be expected that transition curves would be valuable in reducing overall losses. It was difficult, therefore, to see why the Authors considered it "surprising" that the bend with transitions illustrated in Fig. 8b should prove more satisfactory than the circular type shown in Fig. 8a, even allowing for the greater maximum curvature of the type shown in Fig. 8b.

56. It might be possible to evolve a formula for the loss in head in a pipe bend which would take into account the following three main factors:

(*a*) the length of the bend;
(*b*) the radius of curvature; and
(*c*) the rate of change of curvature.

Thus, for an element of the bend:

$$\delta h = \frac{v^2}{2g}\left\{k_0\left(\frac{1}{r}\right)+k_1\left(\frac{1}{R}\right)+k_2\,\frac{d\left(\frac{1}{R}\right)}{d\theta}\right\}\delta l$$

in which: δh = loss of head
v = the mean velocity of flow
r = the hydraulic radius of the section
R = the radius of curvature over the elementary length δl
$\delta\theta$ = the angle subtended by the length δl
k_0, k_1, and k_2 were coefficients depending on the fluid used and on the surface finish of the bend.

57. Dr Allen realized that much experimental work would remain to be done before the formula could be used to estimate the overall loss in a complete bend. However, he suggested it as a possible basis for further investigation, and also to bring out the importance of the rate of change of curvature.

58. In a bend with transitions most of the losses due to the bend would occur in the bend itself, whereas in a circular bend the sudden changes in the velocity distribution would cause additional losses in the straight lengths also.

Mr R. W. Buchanan (Senior Assistant, James Williamson & Partners) referred to the Authors' conclusion that the bend losses observed were generally lower than those reported by previous investigators. This was not true in the case of Davies and Puranik[4] whose results on 4-in.-square teakwood pipes were compared with those of the Authors in Fig. 14.

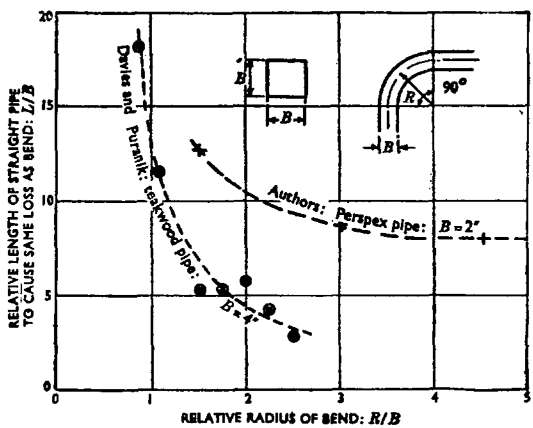

Fig. 14.—Excess loss due to 90° bends in square pipes

60. It could be seen that where the experiments overlapped, the losses given by Davies and Puranik were less than those of the Authors by an equivalent length of about 6 diameters. The main differences between the experiments were:—

(*a*) Davies and Puranik provided only a short approach length of pipe.
(*b*) Davies and Puranik based their losses on pressures measured only 2 diameters downstream of the bend, compared with the Authors' 70–90 diameters.
(*c*) The losses in the 4-in. teakwood pipes followed the V^2 law (f = constant = 0·0047) while losses in the Authors' 2-in. Perspex pipes followed the smooth-pipe law.

Of the three factors, the second seemed most likely to account for the differences in results, and it would be of interest if, to illustrate this, the Authors would give a typical plot of the apparent hydraulic gradient in the developing length downstream of the bend.

61. Mr Buchanan drew attention to an apparent discrepancy between Nikuradse's[10] original curves and the curves plotted in Fig. 3 of the Paper. For example, the critical value of Vm/ν should be about 600 and not 300 as plotted. Would the correction of this affect the position of the Authors' experimental points in relation to the curve for smooth circular pipes?

62. The Authors' results were a valuable addition to the existing evidence that bend losses were a function of the friction factor for the straight pipe. It was reasonable to expect that in very sharp bends, where the flow tended to separate from the boundary to form a vena contracta, a part of the loss would be independent of pipe friction, but this condition did not appear to occur within the range of the Authors' experiments.

Mr Herbert Addison wondered whether the Authors were quite justified in thinking that "pipe roughness does not greatly affect the loss due to a given type of bend" (§ 30). He had himself made experiments directed upon that particular point[15], and in that way he had found that the effect of wall roughness might be to increase the head loss in the bend by 40% or more. In those experiments, the bends were not dissimilar from some of those used by the Authors—they were of square cross-section of 6-cm side (2·36 in.), and the mean radius was 12 cm (4·72 in.). Duplicate sets were prepared. In one, the bends and straight interconnecting lengths were of smooth machined brass, and in the other, they were of unmachined cast iron. This smooth finishing of the internal surfaces of the brass conduits was possible because they were bolted together from separate elements.

64. While it was true that the flow circuit did not include the long straight inlet and outlet lengths of pipe described by the Authors, nevertheless the conditions were identical for the smooth conduits and the rough ones. Yet the overall loss in the cast-iron conduits ranged from 1·35 to 1·54 times the corresponding loss in the brass conduits. Whether this increase was wholly due to the effect of wall roughness was an open question. Manifestly the cast-iron sections could not be aligned as accurately as the brass ones, but as in commercial pipework such imperfections could not be eliminated; they could be regarded as a natural concomitant of rough surfaces.

65. In any event it was unlikely that the effect of wall roughness would be as marked in large pipes as it was in Mr Addison's small experimental ones. In those large conduits the Reynolds number would be much greater and the *relative* roughness much smaller than in the experimental conduits.

66. The velocity-distribution curves plotted in Fig. 10 did not give much support to the view sometimes expressed that the liquid flowing round a pipe bend disposed itself in a sort of free-vortex formation. According to that hypothesis, the pressure head should be greater at the outer wall of the bend than at the inner wall, while the local velocity should be less. On the other hand, this tendency was clearly noticeable in Mr Addison's experiments[16], where the curvature of the bends was relatively sharper than that shown in Fig. 9 of the Paper. By means of pressure tappings drilled in the inner and outer walls of the 90° bends, in a plane set at 45° with the inlet and outlet planes, it was possible to measure the differential head set up as the water flowed round the bends. This measured differential head was rarely more than 1–2% above or below the head computed on the basis of ideal free-vortex flow.

67. Future instructive experiments on the effect of transitions in bends might include investigations on departures from the circular arc other than those chosen by the Authors. For example, in the case of a bend interpolated in a conduit of circular cross-section, there might be a transition from a circular to an elliptical cross-section in the bend itself. Here, perhaps guidance could be obtained from the performance of the draft tubes of hydraulic turbines, which might be regarded as right-angle bends specially designed to give minimum head loss.

The Authors, in reply, observed that Dr Brebner's tests were very interesting and were complementary to those described in the Paper. The Authors were, however, very doubtful whether a downstream straight length of only 30 diameters was sufficient to ensure that the flow had completely settled down after the disturbance due to the bend. In their own investigation they had been misled at first by the many previous investigators who had confidently published results obtained with quite short lengths of straight pipe on either side of the bend and using tapping points quite close to the bend to measure the loss due to it. A great deal of the Authors' work was done initially with a straight of 72 diameters on either side of the bend, but eventually it was realized that the flow was only just becoming completely steady over the 72 diameters upstream so that the friction coefficient could not be measured accurately. Another 72 diameters had to be added to make the measurements accurate enough. Similarly, the least distance for the flow to become steady downstream of the bend was 60 diameters, and it was sometimes more with the sharper bends. Only after another 72 diameters had been added downstream did it become apparent how much error was incurred by using too short a length. A very tiny error in measuring the steady hydraulic gradient over a long length of pipe could, of course, distort very considerably the relatively small apparent loss due to the bend.

69. In this connexion Dr Brebner's Fig. 11 showed an actual grade line which was not quite parallel to the straight-pipe hydraulic grade line. If this Figure was representative of Dr Brebner's results, it fully confirmed the Author's view. However, the Figure was possibly intended to be only diagrammatic.

70. The Authors must also take issue with Dr Brebner on the question of the loss due to the roughness of the downstream pipe. Dr Brebner had used a smooth upstream pipe and bend coupled to a rough downstream pipe. The rougher this downstream pipe, the greater the apparent loss due to the bend. However, the Authors considered that the results might have been completely misinterpreted. If a straight smooth pipe were connected to a rough pipe of the same diameter *without* an intervening bend there would be a change of the velocity distribution as the water passed the joint. This would be inevitable since the rougher pipe would have slower flow near the walls and faster flow at the centre than the smooth pipe for a given total flow. Changing the pattern of velocity distribution would almost certainly be accompanied by a loss of head. Thus at least part of the extra loss of head which Dr Brebner had recorded with rough downstream pipes had probably been associated with the change from smooth to rough pipe and was not associated with the bend at all.

71. Referring to Mr Addison's tests, it was a pity that the value of his experiments should have been reduced by the greater lack of fit of the joints in his rough pipes compared with the smooth. In the Authors' view this could be enough to invalidate the conclusions. In their study of the literature they had come across numerous instances which showed just how much any lack of fit could vastly increase the apparent loss at the bend. Also, if Mr Addison's tapping points were, as he himself had said, too close to the bend, the fact that they were at the same spacing for each set of tests would lead to another possible source of error. It was likely that, for the rougher pipes, more of the extra energy of the water due to spiral flow would be destroyed by friction before it could be gradually converted back to pressure energy. The flow would therefore become steady at a point nearer to the bend. This would mean that the tapping points for the two sets of tests were not really at corresponding points.

72. The Authors stressed the importance of the position of the tapping points and adequate lengths of straight because the test results of Davies and Puranik quoted by Mr Buchanan were among those which the Authors had considered quite valueless. Davies and Puranik appeared to be among the "worst offenders" of all the previous investigators.

73. Mr Addison's measurements of the pressure difference between the outer and inner faces of the bend at a point about halfway round was not very conclusive evidence for the existence of free-vortex flow in his tests. The total pressure difference between

the inner and outer faces round the bend must balance the total change of momentum per second of the water as it flowed round the bend (ignoring the slight inequalities of friction). Thus the pressure difference was purely a function of the square of the mean velocity in the straight part of the pipe, and would be constant whatever the velocity distribution in the cross-section of the bend.

74. The Authors were very grateful to Mr Buchanan for pointing out that the values of friction factor obtained by Nikuradse for circular pipes had been wrongly plotted. This had now cleared up a matter which had worried them. As plotted in the Paper the Authors' results had not been quite parallel to the Nikuradse curve for smooth circular pipes whereas it would be reasonable to suppose that it should be. The Nikuradse curves had now been replotted and the smooth circular-pipe curve was much more nearly parallel to the Author's smooth rectangular-pipe curve. The replotting also had the effect of making the friction factor 20% lower for the rectangular pipes than for the circular, whereas it had originally appeared to be about 10% lower.

75. Dr Allen had suggested a probable form of the relation between head loss and the various parameters of the bend. His suggestion was most interesting and valuable. But he was also right in saying that much experimental work would be needed to establish the relation fully. Although the Authors' results had only covered a very narrow field they had been enormously time-consuming, because of the high degree of accuracy required if tests of this nature were to give reliable results.

References

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16. Herbert Addison, "The use of pipe bends as flow meters". Engineering, vol. 145 (1938), p. 227.