BRANCHING FLOW IN LARGE CONDUITS

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INTRODUCTION

This paper, and the paper by Jamison and Villemonte, "Pipe Fitting Losses in Laminar Transition Flows", represent a progress report on the activities of the Task Committee on Branching Conduits. The paper will present the result of investigations on the subject of head losses for dividing flow with special reference to large hydraulic conduits. No discussion on the subject of pressure fluctuations and pressure effects in conduits will be given. It is planned that future investigations will expand in the direction of uniting and other combinations of flow, as well as application to air ducts, the use of guide vanes, the length of a branch from pump or turbine to the manifold, and the influence of branch spacing.

The lack of reliable design data for determining losses through hydraulic conduit branches has resulted in a great deal of experimentation and numerous papers to be written on the subject. Since the type of branches vary widely from large air-distribution systems through major hydraulic conduits to small plumbing fittings, attempts of experiments to arrive at general solutions have been few. Most experimental work has therefore been directed at liquids flowing at low velocities in small diameter pipes, large conduits such as for hydroelectric schemes, or air conditioning systems.

The British Hydromechanics Research Association[1], has conducted a review of literature on the division and combination of flows in closed conduits, with the support of the Central Electricity Generating Board, Great Britain. This is a comprehensive review of the subject and provides abstracts of most literature (over 60 references) dealing with branching flow.

In general the nomenclature and terminology used in this paper and planned for future papers on the subject conforms to that recommended by the British Hydromechanics Research Association report. The terminology used for the various configurations is shown on Fig. 1.

BRANCHING CONDUIT INVESTIGATIONS

GENERAL SCOPE

The purposes of investigations on branches are to determine fluid losses; pressure fluctuations, whether to determine high or low (cavitation values); and the relation of hydraulic losses to structural considerations in large conduits, particularly as they influence economics. Generally, losses at branches are relatively minor, but they become significant under certain conditions, such as low head cooling water systems in power plants, and in hydroelectric conduits where the value of the loss of power may be considerable. In these cases individual efforts are made to reduce losses by modifying the branches. On the other hand, air conditioning systems usually consist of a variety of standard ducts and bends selected and assembled to meet a particular specification. Higher losses are often tolerated in the interest of ease of manufacture or assembly.

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1 - All such numbers refer to the Bibliography.

METHODS

The methods of investigation which have been performed to determine losses at conduit branches include the following:

Theoretical.

Experimental - General.

Experimental - Specific.

Prototype Tests.

Theoretical.

Theoretical investigations can be further divided into the use of the free streamline theory and the use of the momentum principle.

1. Free streamline theory.

This theory is based on the flow having a boundary which is a streamline at constant pressure. The way this theory is usually applied to divided flows in closed conduits is to analyze the situation where the flow emerges through a slot or orifice in the side of a pipe. Having established the theoretical shape of the issuing jet it is considered that the pipe walls should follow the curve of the free streamlines as closely as possible to reduce the loss.

Results from this theory had been confirmed by experiments[2,3] for very simple flow configurations and difficulty of application occurs with more elaborate fittings which are known to give lower head losses. The inclusion of tapered entrances to branch pipes, rounded corners, and guide vanes complicates the problem beyond the scope of the technique.

2. Momentum principle.

The use of the momentum principle provides a more successful approach to the theoretical analysis of losses at branches and the results from these analyses usually agree well with experimental results.[4,5] The losses are assumed to be partly due to the deflection of flow and partly to the re-expansion of the stream from a vena contracta formed just after the branch. As with the free streamline theory, this technique cannot predict the performance if improvements are obtained by rounding corners or tapering the entry sections to a branch.

Experimental - General.

Early, and probably the most important, experiments conducted for dividing and uniting flows were those carried out at the Hydraulic Institute of the Munich Technical University from 1928 through 1931.[6,7,8,9] In 1957 Gardel[10] carried out a similar range of experiments at Lausanne. Other experiments of a general nature were performed at the Iowa Institute of Hydraulic Research.[11]

Branch ducts for air distribution systems were investigated by Konzo et al in 1953[12] for various takeoff angles. The apparatus, being manufactured from sheet metal with soldered joints, is not comparable with the carefully machined components used in the Munich experiments, but the results help to confirm the earlier work.

Experimental - Specific.

Many reports exist on hydraulic model tests of proposed civil engineering projects. The tests are generally related to the specific model and do not result in any numerical data or formulae of a general nature, they do however provide an indication of what improvements or modifications may help to reduce losses, and in some cases result in a standard type design.[13,14,15] In general the model tests considered in this paper are concerned either with power station cooling water systems[16] or bifurcations in hydroelectric penstocks or dam outlet works.[17,18,19,20]

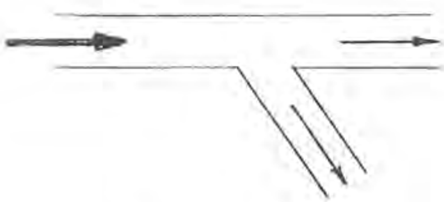
Prototype Tests.

Few tests have been carried out on constructed conduit branches. Those performed by Sulzer at Lucendro Power Station[17], and by Escher Wyss at Olivone Power Station[14], indicate reasonable consistency between the model and the prototype measurements.

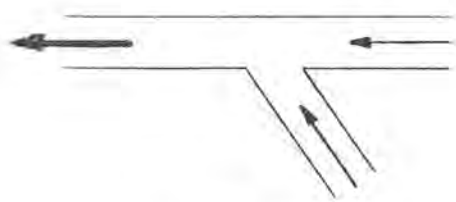
TYPES OF FLOW

The types of flow which had been investigated are as follows:

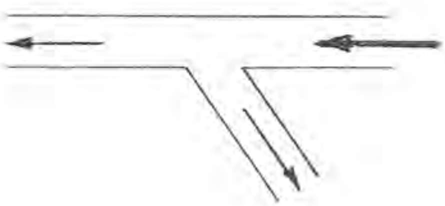
Dividing



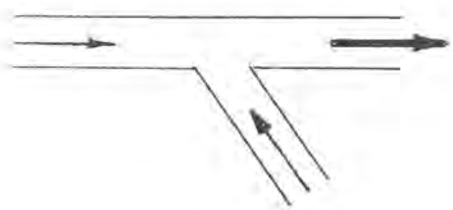
Uniting



Reverse Dividing



Reverse Uniting



DETERMINATION OF LOSSES

VARIABLES AFFECTING LOSSES

General Geometry.

General geometric considerations which will affect losses from branching flow are related to whether the condition is an individual branch, wye, bifurcation, trifurcation, manifold, or plenum, and in the case of multiple branches, depends on the closeness of the branches.

Branch Geometry.

The principle variations in branch geometry include:

1. Angle of branches

2. Cross-sectional area of branches

3. Shape of cross-section of branches

4. Aspect ratio of cross-sections

5. Roughness

The inclusion of all the parameters needed to describe such devices as filler blocks and deflectors, complicates the problem to an unreasonable degree.

Flow Conditions.

For a given branch of fixed geometry losses are effected by whether the flow conditions are:

1. Dividing, uniting, reverse dividing, or reverse uniting flow.

2. Proportion of total discharge flowing in each branch (Q_b/Q_m) or V_b/V_m.

3. Inlet conditions which affect velocity distribution, swirl, asymmetry, etc.

4. Outlet conditions.

To eliminate these last two variables for experimental purposes, it is necessary to provide long straight pipes upstream of the branch to establish fully developed flow at the inlet; and downstream to allow the flow to become fully developed after passing through the branch. In a number of the experiments which have been performed, it is questionable whether these conditions were arrived at.

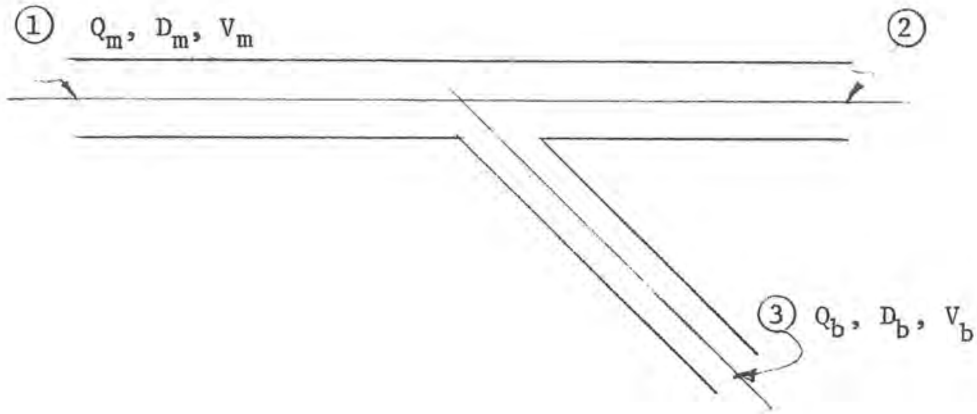
Fluid Properties.

Fluid properties include Reynolds Number and the Mach Number of the flow. For hydraulic conduits the flow will be incompressible and the Mach Number can be ignored, but in cases where model tests using air are carried out at high Reynolds Number the Mach Number will become significant.

Most experimentors have concluded that the loss coefficient is independent of Reynolds Number, but their tests have usually been confined to values of 10^4 to 10^5. Ruus[21] concludes that losses increase with increasing Reynolds Number which tends to substantiate the results of tests of the Boulder Canyon Project.[18] However, this increase does not appear to be significant. Furthermore, it is not clear if the reduction in loss observed is due to the increase in Reynolds Number obtainable on a larger model or the inevitable change in roughness between one model and another, or between model and prototype. Certainly the latter effect could be significant if results from small scale models such as used at Munich are extrapolated to large hydraulic conduits.

EXPRESSION FOR LOSSES

A number of ways of expressing the loss at a branch may be used, but certain techniques have received general acceptance. The changes in total head should be measured and this involves observation of both the static pressure and kinetic energy of the flow at sections before and after the branch. The complication of an unknown velocity profile can be avoided by choosing sections having fully developed flow where the error in calculating velocity heads using mean velocity is small. In practice, this can be achieved by providing long straight lengths of pipe before and after the fitting. Measurements are then made at the inlet to the fitting and at a section sufficiently far downstream for flow to again become fully developed. The head loss will be partly due to losses in the actual fitting and partly due to pure friction losses between the measuring sections, and the friction loss should be calculated and subtracted from the measured head loss. Losses due to a particular fitting are then derived as shown below.



The following symbols are used:

h_p = pressure head

h_b = loss of head in branch

K_b = head loss coefficient in branch expressed in terms of velocity head in main $(h_b / \frac{V_m^2}{2g})$

h_m = loss of head in main due to branch

K_m = head loss coefficient in main expressed in terms of velocity head in main $(h_m / \frac{V_m^2}{2g})$

h_f = friction head loss

$$h_b = h_{p_1} - h_{p_3} + \frac{V_1^2 - V_3^2}{2g} - h_{f(1-3)}$$

$$h_m = h_{p_1} - h_{p_2} + \frac{V_1^2 - V_2^2}{2g} - h_{f(1-2)}$$

Q_m, A_m, D_m & V_m are the discharge, area, diameter (where applicable) and velocity in the main; and

Q_b, A_b, D_b & V_b are similar parameters for the branch.

To obtain a non dimensionless loss coefficient the loss may be expressed as a proportion of the velocity head either in the main pipe or the branch pipe. The loss coefficient as stated herein is related to the velocity head in the main pipe carrying the total discharge (that is upstream in the case of dividing flow and downstream in the case of uniting flow). The dividing flow is used as the standard and thus for some arrangements of flow "negative losses" would be measured. "Negative losses" may also result due to the assumption that mean velocities are assumed but an unsymmetrical velocity distribution occurs at the point of measurement.

In general loss coefficients reported in the literature are usually plotted against the discharge ratio Q_b/Q_m, a separate curve being plotted for each branch tested. In the case of branches which are similar except for the ratios of cross-sectional area of main to branch, a simplification may be made by plotting the coefficients against the velocity ratio V_b/V_m. This automatically takes into account the different areas and the performance of the various branches can be represented on one basis. Since essentially all of the branches reviewed in this paper are for circular cross-sections all losses have been plotted against the velocity ratio.

DIVIDING FLOW

SCOPE OF THIS INVESTIGATION

This paper will deal with the subject of dividing flow only and is oriented toward flow in branches for large conduits such as found in dam outlet works and power conduits. Most of the important work on the subject has been reviewed.

Important considerations which are not discussed in detail in this paper are the influence of the closeness of branches on losses and downstream velocity distribution. A secondary, yet very important consideration in the case of power conduits, is the effect of a branch close to a turbine on the velocity distribution entering the spiral case which may cause a marked change in the unit efficiency. Information on this latter subject appears to be very sketchy.

GENERAL EXPERIMENTS

Munich.

A series of model junction tests covering tees, and 45° and 60° branches, for diameter ratios D_b/D_m, .35, .58 and 1.00 for each of these angles, were carried out at the Munich Technical University from 1928 through 1931.[6,7,8,9]

In all cases the main pipe was cylindrical with a diameter of 43 mm (1.7 in.); the smallest branch was 15 mm (0.59 in.). For each branch angle and diameter the junction of the branch and main had three forms: Form 1 - cylindrical with sharp edges; Form 2 - cylindrical with edges rounded to radius $R = 0.1\ D_b$; Form 3 of Types I and II - conical transition with cone angle of 12°40' and average length of taper 2 D_b to 2-1/2 D_b; Form 3 of Type III had edges rounded to $R = 0.2\ D_b$ (no conical transition). The loss in the branch and along the main were determined for dividing flow and uniting flow. Some runs were made with reverse dividing and reverse uniting flow. Experiments were carried out over a limited range of Reynolds Numbers (5×10^3 to 1×10^5). The most significant conclusion was that for a given configuration the loss coefficient was found to be a function of the ratio of flow in the branch and main pipe but independent of the total discharge (i.e. Reynolds Number).

The early tests were carried out with iron pipes; in the later investigation brass tubes were used. It was recognized that some deterioration had occured in the pipes which were used earlier and the later experiments listed conditions that had probably interfered with the initial tests and described adjustments in the equipment for the later tests.

These tests showed that by reducing the angle of the branch from 90^o to 60^o or 45^o, a significant reduction in head loss resulted. Head loss is markedly affected by excessive improvements of rounding the edges at the junction of the branch and providing a conical transition. Experiments conducted on three angles of transition cone showed that an angle of about 13^o is the best.

Fig. 2 shows the shapes which were tested at Munich. The head loss coefficients for Form 1 (cylindrical with sharp edges) are shown on Fig. 3, and for Form 3 (conical) on Fig. 4. The losses for Form 2 (cylindrical with round edges) lie between these two sets of curves. Typical values of the loss coefficient in the main (K_m) are represented by those for the 60^o branch.

The later Munich experiments included a test to measure the losses (K_b), at a 45^o wye branch Type II, Form 2, with subsequent two - $22\text{-}1/2^o$ miters for a total deflection of 90^o, the bend being arranged at various distances from the main pipe and with different segmental lengths. In the range of Q_b/Q_m less than 0.4, the most compact arrangement was near the hydraulic optimum, and showed an insignificant increase in loss due to the bend.

<u>Gardel (Lausanne).</u>

In 1957, Gardel[10] conducted a series of experiments similar to Munich at the Hydraulic Laboratory of the Polytechnical School of the

University of Lausanne. An investigation was made of the head losses for five different ratios of diameter (D_b/D_m = 1.00, 0.83, 0.67, 0.53, and 0.40) for a 90° branch, and for D_b/D_m = 1.00 for a 60° and 45° branch. Studies include both dividing and uniting flow and attempts were made to establish general equations for calculating head loss.

The main conduit was 150 mm (5.9 in.) and the branches varied from 150 mm to 60 mm (about 2 in.). Sufficient length of pipe was installed upstream and downstream of the branch so that an accurate hydraulic gradient could be established. The branches were apparently fabricated with asbestos-cement pipe and were therefore relatively rougher than the carefully machined tubes of the Munich experiments. The junction of the branch and main conduit was rounded with small radii. From the data presentation it appears that the radii were random and were measured after the tee was cast and the interior surfaces smoothed. The maximum Reynolds Number was about 4×10^5.

For the general equation to determine the loss coefficients Gardel used a theoretical approach derived by Professor Favre[4]. Although the theoretical derivation was developed for uniting flow, Gardel proposed empirical equations using constants derived from his investigations. The experimental results generally lie closely along the curves of the empirical equations, indicating that the form of the equation is generally accurate.

The shapes studied at Lausanne and the head loss coefficients are shown on Fig. 5.

Comparison of Munich and Gardel Tests.

The observations of Gardel and Munich (Form 2) are compared on Fig. 6. Values for K_b correspond closely for a branch having a diameter equal to that of the main regardless of the branch angle. However, Munich shows significantly greater values for the lower ratios of D_b/D_m (.58 and .35) than the comparative Gardel results for D_b/D_m = .53 and .40. The difference is marked with higher velocity ratios. Further, Gardel shows that for a 90^o tee the values of K_b do not change significantly with varying ratios of diameter. On the other hand, the Munich results show a relatively large change with variation in diameter.

Additional Experimental Investigations.

1. Iowa.

In the absence of a general analysis of manifold flow laboratory studies were conducted at the Iowa Institute of Hydraulic Research at Iowa City, Iowa and are comparable to, but not as comprehensive as, those conducted at Munich. Results of these investigations are reported by McNown.[11] The studies were made for both dividing and uniting flow. Mr. McNown has related the various occurrences with conventional equations of energy and momentum. Theoretical and experimental results coincided closely for dividing flow.

Coefficient of losses in the branch and the main were obtained for 90^o sharp edged junctions with diameter ratios, D_b/D_m, of 0.25, 0.50 and 1.00. The main was 2-in. diameter and the branches were 2-in., 1-in. and 1/2-in. diameter brass pipe. Sufficient length of pipe was provided upstream and downstream from the junction so the friction loss of the pipes could be isolated.

The values of K_b for Munich for cylindrical branches with sharp edges and D_b/D_m = 0.58 are compared with the Iowa experiments for D_b/D_m = 0.50 on Fig. 7. It can be seen that considerably larger loss coefficients are shown by Munich. Although not shown, a comparison of Munich with D_b/D_m = 0.35 and Iowa for D_b/D_m = 0.25 shows values a little closer together but the difference is still considerable. Only with the branch and main of the same diameter is there reasonably close agreement between the two results.

This comparison leads to conclusions similar to those discussed in comparing Gardel and Munich observations. Also, as found with Gardel, the results of the Iowa experiments show that there is little change of the head loss coefficient from variations in diameter of the branch, which is not the case for Munich.

2. Stanford.

Tests were conducted at Stanford Hydraulic Laboratory at Stanford University[11] on five sharp edged 90^{o} tees. The diameter of the main was 1.276 in. and the branch sizes were selected such that the diameter ratios D_b/D_m were 0.294, 0.392, 0.490, 0.642 and 0.830. These experiments were conducted to attempt to reconcile apparent conflicting results between the Munich and Iowa experiments.

The trend of the curves confirmed the data obtained at Iowa. A typical result is shown on Fig. 7 in which the Stanford experiments for $D_b/D_m = .49$ may be compared with Iowa for $D_b/D_m = 0.50$. Also as can be seen the Gardel results for similar diameter ratios but with rounded edges fall a little below Iowa and Stanford.

3. Boulder Canyon.

As part of the hydraulic investigations for the Boulder Canyon Project, model studies were made of the penstock and outlet works by the United States Bureau of Reclamation (USBR) in the Hydraulic Laboratory of the Colorado Agricultural Experiment Station at Fort Collins, Colorado.[18] One section of the above report was devoted to the description of hydraulic investigations of one branch of the penstock for both uniting and dividing flow. The study was also expanded to determine the loss in two configurations of a 90° tee. The main conduit was 10 in. diameter for all tests. The branch was 4.33 in. for the 75° branch and 2.49 in. for the 90° tests. The 75° test, was performed with conical transitions on the branch. The 90° tests were conducted as control tests; one branch junction being cylindrical with sharp edges and the other conical, so that they could be compared with the Munich experiments.

The results of the control test for the cylindrical sharp-edged branch are shown on Fig. 7. The head loss coefficients for the control test agree reasonably well with Iowa, but are significantly below Munich. Similarly, control tests on a branch with a conical transition for the tee show that the USBR values are about one-third of Munich.

In the report of the Task Force on Flow in Large Conduits of the Committee on Hydraulic Structures[22], reference was made to coefficients of head loss at bifurcations as obtained from E. Mosonyi[23] for dividing flow.

Mosonyi makes no reference to the source of his data, but W.A. Mechler[24] in a discussion of the Task Force paper reveals that the Mosonyi data falls essentially exactly on the curves presented by Munich. One discrepancy apparently is that the 30° angle of Mosonyi should be 45°. Mr. F.W. Blaisdell in a discussion of the same paper[25] points out another ambiguity in the Mosonyi data in that the head loss coefficients are meant to be related to the velocity head downstream of the bifurcation (and not in the main as for Munich), and are supposed to give the pressure head change (and not the change in the total energy gradient as for Munich). However, since the Mosonyi information agrees quite closely with Munich there is some doubt as to its accuracy and its use is not recommended.

TESTS ON SINGLE BRANCHES

Lucendro.

A carefully executed test program was conducted at the Lucendro Power Station in Switzerland[17] by Sulzer to determine the head losses in a section of a 1.10 m diameter welded steel penstock containing two 55° branches. The branch tested was 0.80 m in diameter, and consisted of a conical rounded transition. The head loss coefficients were measured at various points under a complete range of discharge for dividing flow, and were compared with the results of model tests.

The values are shown in Fig. 8 and indicate that the model tests results are close but a little higher than those found in the field. The reasons advanced for the difference were attributed to the higher Reynolds Number, the lower relative roughness and the rather more favorable diameter ratio of the plant. Both the model and field tests showed that a marked increase in head loss occurred in the branch with higher velocity ratios, that is most of the flow in the main passing through the branch.

USBR.

Hydraulic model studies were made of the Fontenelle Dam outlet works in the USBR laboratory.[19] This study was of the overall outlet works arrangement and not a specific study of branching flow. A 60° branch with the same diameter as the main conduit and two configurations was studied. In the first the branch and the main conduit intersected in a sharp corner; for the second the branch was accomplished with a series of mitered cuts. The conduits were 4.86 in. diameter. Pressure head measurements were obtained about two diameters upstream and six diameters downstream of the branch intersection. No attempt was made to isolate the friction loss from the branch loss. The tests show that the mitered branch reduced the head loss by about 50%.

The head losses with sharp edges at the junctions compare favorably with corresponding Munich results. Loss coefficients with the mitered turnout are shown on Fig. 8 and appear to fall a little below the Munich results for a conical transition with the same angle.

The tests on the Boulder Canyon penstock have been described previously. The values of K_b for the conical transition with $D_b/D_m = 0.43$ and a 75^o branch are shown on Fig. 8. The results compare well with Munich values for a 60^o branch and $D_b/D_m = 0.58$, being slightly less in the upper range of velocity ratios and slightly higher in the lower range.

Escher Wyss.

A new type of design for penstock branches, with a crescent shaped internally located reinforcing rib, was developed by Escher Wyss in 1955 for large penstock and discharge lines, and improved over a period of about ten years.[13,14] The new design, an Escher Wyss patent, has been developed from structural considerations to result in branch reinforcement with an element subject essentially only to tensile stresses as distinct from the normal external rib which is subject to considerable bending stresses.

Beginning with the branch pipe of the conventional type with external reinforcement as shown on Fig. 9a and 9b, an improved design evolved after intensive investigation, in the form of a crescent shaped rib inside the branch pipe. With such a rib of the theoretically ideal shape the tensile stress is reputed to be uniformly distributed and to have almost the same magnitude as the stress in the shell sections of the pipes adjacent to it. The structural efficiency of the junction is developed by widening the conduit at the intersection somewhat, to provide conical or elliptical shapes which are able to resist the internal pressure by membrane action rather than by bending. A typical branch pipe with internally located reinforcing is shown for the Sils Manifold on Fig. 9c. The stress distribution for the external ribbed reinforcement, and the internal crescent shaped reinforcement as developed by Escher Wyss, can be compared on Fig. 9b and 9d, respectively.

The design with an internally located reinforcing rib provides various advantages for the construction of powerhouses. The elimination of external reinforcing members reduces the excavation for underground chambers which will house a steel penstock, and eases the difficulty of transporting these large members through an access tunnel to the underground powerhouse. This is particularly noticeable in plants operating at higher heads since construction for this type usually requires extensive external reinforcement. The reduced external dimensions enable relatively large branch parts to be transported as a single unit so that a fully fabricated branch can be stress relieved during fabrication. Even in case of large dimensions it is possible to restrict field welding to girth welds only, which would be carried out on simple pipe sections with relatively small pipe thickness. The field welds can, if necessary, be annealed by inductive or electric-resistance heating methods. The branch including the rib can be welded and stress relieved in the shop. A further advantage is that in the case of branch pipes embedded in concrete within a rock excavation, a proportion of the internal pressure can be transferred to the rock because the branch pipe expands like a uniform cylindrical pipe on all sides whereas such expansion is restricted by the use of an external rib and collars. Moreover, elimination of the external members improves consolidation and facilitates placement of concrete.

Escher Wyss has performed a number of structural and hydraulic model tests on large scale models. By using models tested with air the head loss at each stage of development was checked. The final design of the entrance to the branch and the internal rib is compared with the original arrangement for external reinforcement on Fig. 10a. The structural necessity for developing strongly conical sections at the junction also assists in providing good hydraulic conditions. The final arrangement results in the internal rib being outside the cross-section of the flow in the main pipe whether it is dividing (as in the case of generating) or uniting (as in the case of pumping).

The head loss coefficients K_b and K_m for the externally reinforced and the final internally reinforced branch are shown on Fig. 10, together with the Munich coefficients for a 45^o conical section with $D_b = .58\ D_m$. Tests have apparently also been made for uniting flow (pumping mode) but no information was given.

Field measurements were made on the Olivone Power Plant and compared with head loss coefficients obtained in the laboratory. The arrangement consists of four branch pipes from one manifold and head loss measurements were made on each branch. Reasonable consistency was obtained between the measurements in the field, tests on the completed model, and tests on single models, as shown on Fig. 10b. The reason for the relatively small losses in the first full scale branch, resulted from the flow distribution caused by the bend before the manifold which could not be rebuilt in the scale model.

Krupp.

The Krupp Company in Rheinhausen, Germany has also developed a penstock branch construction which omits all exterior ribs and collars, using the principle of self-supporting shells.[15] Patents covering this new design have been registered in a number of countries.

In this design the branch pipes are built of self-supporting shells using only circular cones and spheres. All intersection lines between individual shell components are shapes in one plane, either circles or ellipses. The conical shells of the branch pipe run tangentially toward a spherical shell the center of which is located in a structurally optimum position. Consequently, the stresses imposed on the structure are predominantly membrane stresses.

A junction using this system, rather than external reinforcement, has the same advantages as described previously for the Escher Wyss arrangement. This particularly applies in the case of underground construction. On Fig. 11 a typical wye is shown for this system both for a model and the as-built structure.

Because of the potential loss of hydraulic head through the spherical section, model tests were conducted to examine the effect of various guide plate shapes to be inserted in the sphere. In designing these guide plates, particular attention was given to constraint free installation and free expansion clearance of the branch pipes. The guide plates are bolted to a supporting cylinder attached to the spherical cap of the branch pipe, and held by individual clips around their periphery. They can move freely in these clips so as to permit free expansion of the pipe shells. Typical model arrangements which were tested for wyes and branches are shown on Fig. 11c. Form a represents a condition with the spherical junction with no inserts; Form b with inserts; and Form c with a constant flow cross-section which was considered to be the most hydraulically favorable shape. No particular details are available on the methods and equipment used in these model tests. Head loss coefficients based on the velocity head in the main, were found only for conditions of full and zero flow in the branches, both for uniting and dividing flow where applicable. The resulting values of K_b for the wye are plotted on Fig. 13; similar information was not available for dividing flow for the branch.

Comparison of Tests.

Values of K_b are compared on Fig. 8 for the branches discussed together with comparable Munich tests and the Escher Wyss branch. In general good agreement is shown, with the possible exception that the Lucendro tests result in higher coefficients than shown by the other experiments for velocity ratios in the range of 1 to 2. The results of the Escher Wyss branch investigations are generally well below the other tests.

TESTS ON WYES

Ruus.

An extensive series of tests with a variety of lucite wye models of conical and spherical shapes were conducted in the Hydraulics Laboratory of the Department of Civil Engineering at the University of British Columbia, by Eugen Ruus in 1969.[21] The purpose of these tests was to determine the influence of the angle of bifurcation, and the size of a tie rod, on head losses in conical wyes, and the influence of the size of sphere in spherical wyes. Some tests were also conducted to determine the affect of length of the conical transition section on the head losses in the wye. A summary of the principal results is shown on Fig. 12.

Five conical wyes were tested, three of which had an angle of bifurcation of 60^o. For the remaining two wyes the bifurcation angles were 45^o and 90^o. The angle of bifurcation for the two spherical wyes was 90^o. Tapering of the cones was done at an angle of 8^o and 10^o. The pipe sizes were invariable throughout with the main being 5-1/4 in. diameter and the branches 3-3/4 in. diameter. All tests were performed for dividing flow. The main pipe had a length-diameter ratio of 75 to ensure a symmetrical velocity distribution at the entrance to the wye and equal flow in individual branches. The branches had a length-diameter ratio of 30. Despite the care with which the experiments were conducted, as has been found by other experimentors, for symmetrical flow conditions for both wye and manifold arrangement, the head loss in water flowing into one branch was substantially different from that of the other due to the preference for the water to enter one particular branch.

The results show that the values of K_b are very close for a particular angle whether a wye or manifold arrangement is being tested. Values for the 90^o angle are generally significantly greater than the 45^o and 60^o angles; the 60^o angle however shows the lowest loss. The loss in the manifold was found to be less than the sum of the losses in the wye and bend. Significant increases in head loss are caused by a tie rod, the increase in head loss being approximately proportional to the diameter of the tie rod. To reduce the head losses in a spherical wye it should be made as small as structurally feasible. The rounding of edges of junctions between the sphere and the pipes has a substantial influence on head losses. Head losses caused by spherical wyes are considerably larger than for conical transitions, and the losses with the large spheres significantly exceed those with tie rods. The observations show that the head loss coefficients are affected by Reynolds Number. As the value in the main pipe falls below about 3×10^5 to 4×10^5, a decrease in the head loss coefficient results. This can be relatively significant as Reynolds Number becomes 1×10^5 or less.

For comparative purposes, the values obtained by Krupp for spheres without inserts are plotted on Fig. 12. Since the sphere used in the Krupp branch would be defined by Ruus as a large sphere with rounded intersections, the values given by Krupp are considerably lower than would be expected, but the tests carried out by the latter were not as complete as the Ruus experiments.

Salvesen.

In the period 1961-62, Mr. F. Salvesen performed measurements of head losses for dividing flow on a wye model in the Water Power Laboratory at the Norwegian Institute of Technology.[26] The wye tested had an internal rib similar to the principle used in the Escher Wyss design. At the junction however, the wye is widened, not unlike the method used by Krupp. Various projections of the internal rib were tested. The reinforcement rib for the prototype is made of a thick steel plate with connecting fillet plates to obtain a hydraulically favorable form.

The model was made of plastic, the main having a diameter of 278 mm (11 in.) and the branch 180 mm (7 in.). The entrance pipe to the wye had a length of 32 times the diameter and the length of a branch section was 22 times the diameter. In all a total of six rib sizes was tested, including a plain rib without fillets, through a full range of discharges.

The hydraulic losses in all cases are very small. Negative losses which were observed are assumed to be the result of a variation in the velocity distribution from that assumed. The values of K_b are shown on Fig. 13 for the largest rib with fillet plates.

Causey.

Model studies were made on a symmetrical wye branch of an outlet work for the Causey Dam in the USBR Hydraulic Laboratory.[20] The branch was a part of an overall study of the outlet works configuration for dividing flow. No attempt was made to have long lengths of pipe downstream of each leg and as a result the pressure head measurements were made too close to the branch to permit evaluation of the junction losses. Also included in the head loss measurement was a short circular to rectangular transition at the downstream end of the wye. The main conduit was represented with a 4.73 in. diameter pipe and each leg of the branch was 3.55 in. in diameter, the angle between the branches being 60°. The head loss coefficients are shown on Fig. 13.

Comparison of Results.

The tests on the Krupp wye were described previously. The values of K_b for the wyes discussed are compared, together with the values for the Munich and Escher Wyss branches, on Fig. 13. In general it can be seen that the losses in the wyes are relatively low except for Causey, which shows a marked increase above a velocity ratio of one. Apart from this all values lie well below the Munich coefficients for a conical branch of about the same angle and diameter ratio. The values for the Escher Wyss branch compare favorably with the wyes. It is noted that the results by Salvesen do not reflect a marked increase in coefficient with higher velocity ratios as is shown by other tests throughout.

CONCLUSIONS

For the case of dividing flow the conclusions are as follows:

1. The values for branch losses (K_b) obtained from the Munich tests are too high, particularly for angles less than 90° and diameter ratios less than one.
2. The results from Iowa are recommended for tees with sharp edged cylindrical junctions.

3. The information obtained in the Gardel tests, although not as comprehensive as Munich, is generally considered suitable for practical application, but will give results too low for sharp edged cylindrical junctions.

4. Munich values for conical junctions are considered reasonable, even if somewhat too high.

5. Munich, or Gardel, values of loss in the main due to the branch (K_m) are recommended.

6. Losses for 45^o and 60^o branches are generally about the same, but are significantly less than those for a 90^o branch. Variation in loss with the diameter ratio is of less importance.

7. The effect of a bend directly below a branch on the head loss is relatively insignificant.

8. The angle of a conical transition should be between 10^o and 15^o to obtain the least loss.

9. Head losses in wyes appear to be generally less than those found in single branches. Data provided by Ruus should be used for V_b/V_m from 0 to 2.

10. Head loss coefficients at prototypes are likely to be less than those obtained in model tests.

11. For larger conduits of special design, it is practical to obtain a structurally efficient and economical section and at the same time to reduce head losses even below those determined for a normal branch.

12. Relatively large losses will be caused by an internal tie rod, or a spherical junction if special inserts are not added to improve the hydraulic efficiency.

13. More analysis is needed to determine the effect of spacing of branches on loss, and the effect of uniting flow, such as experienced with reversible operation of pump-turbines, in the specially designed intersections for large pipes.

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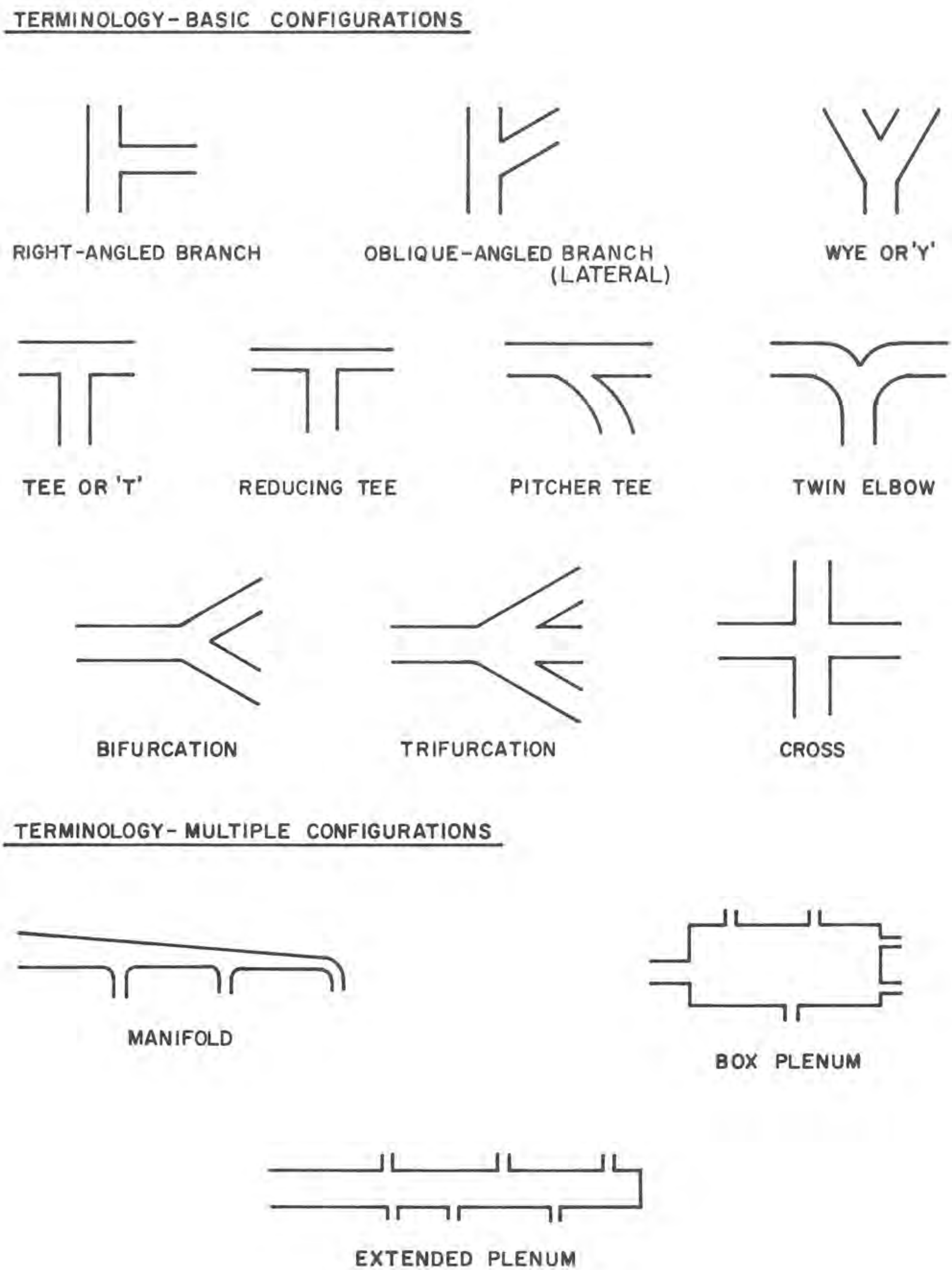


FIG. I. - TERMINOLOGY

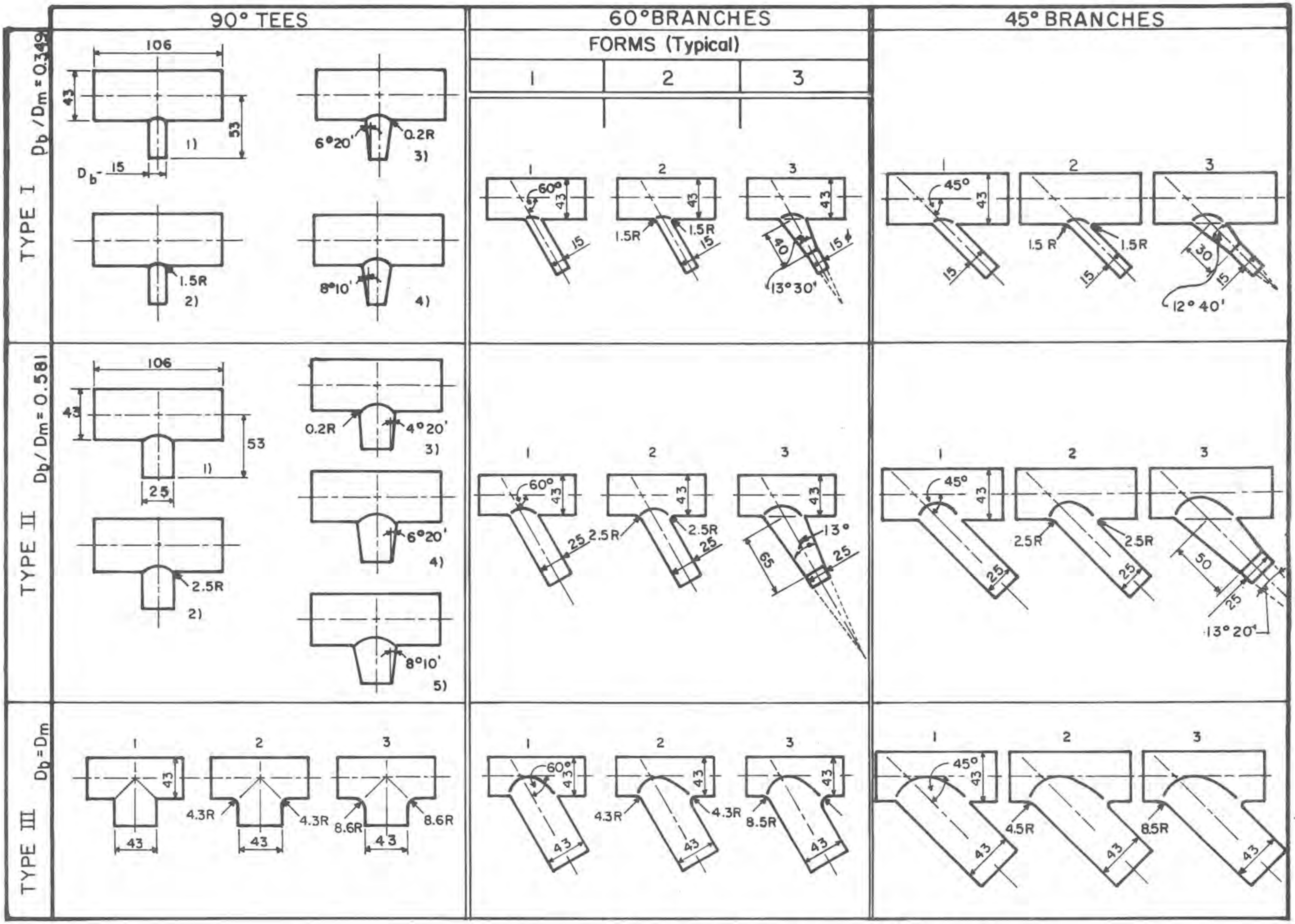


FIG. 2 — MUNICH SHAPES

All dimensions in mm

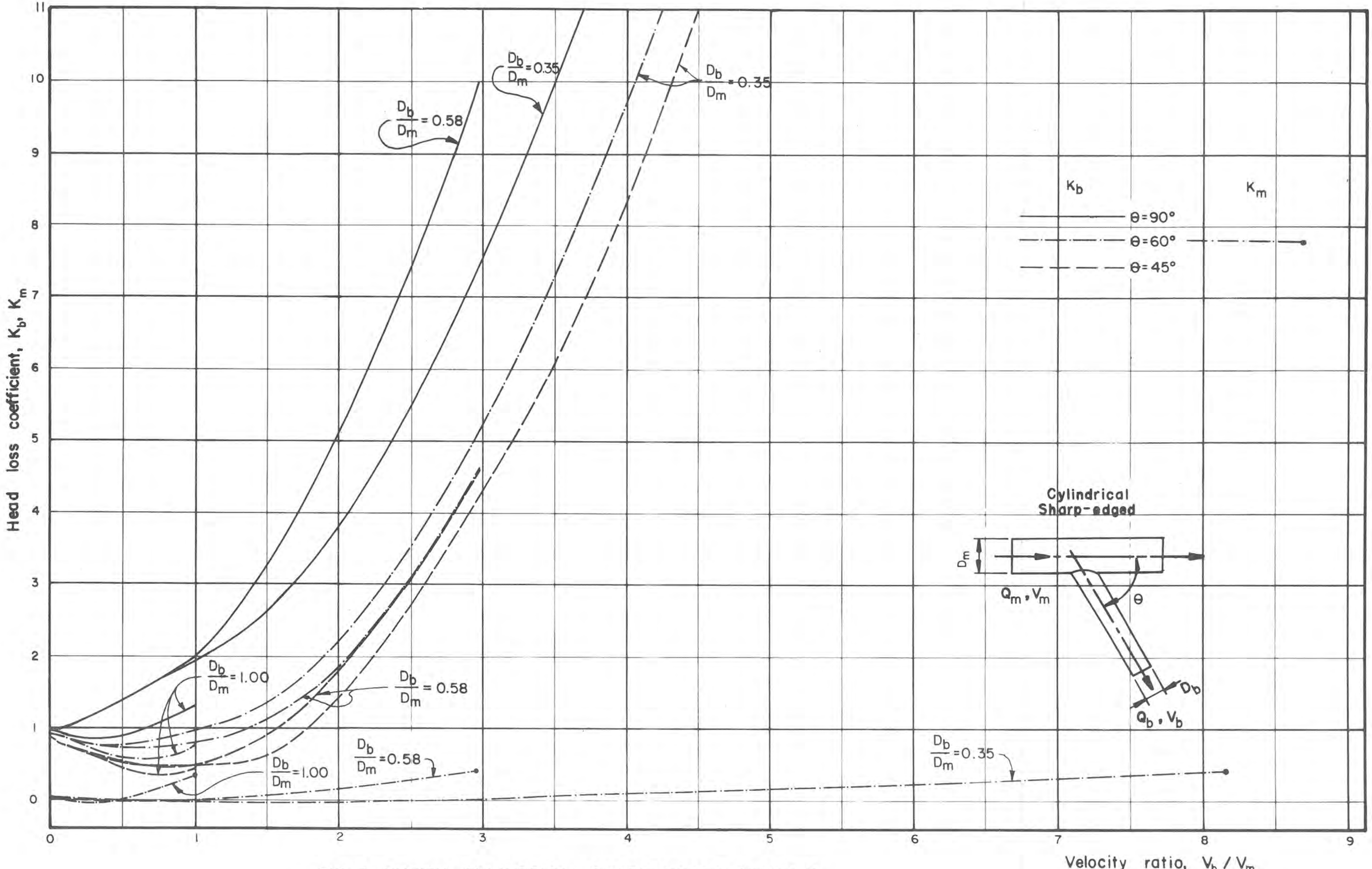


FIG. 3.- MUNICH - CYLINDRICAL, SHARP EDGES (FORM I)

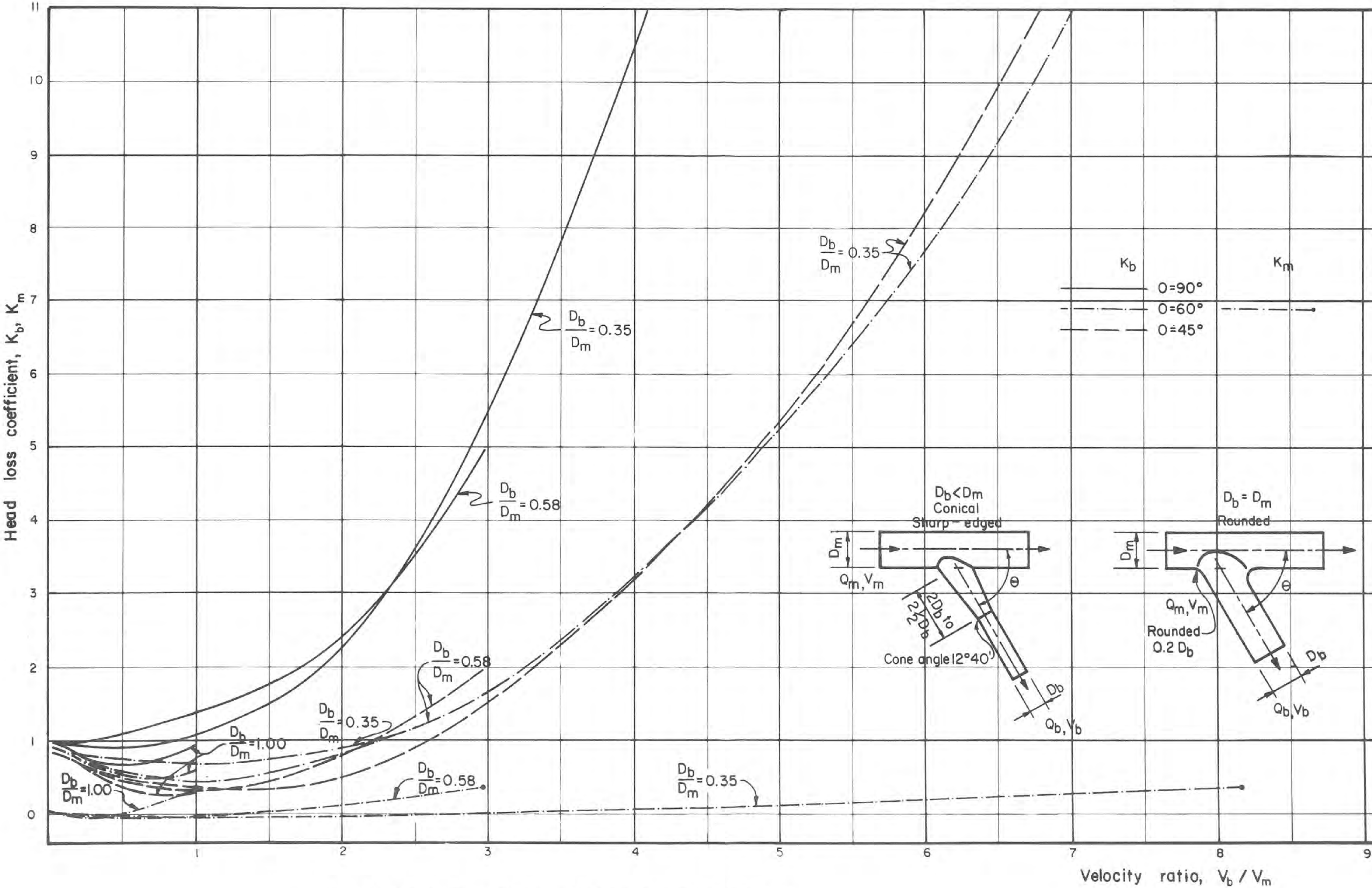


FIG. 4.- MUNICH-CONICAL, SHARP EDGES (FORM 3)

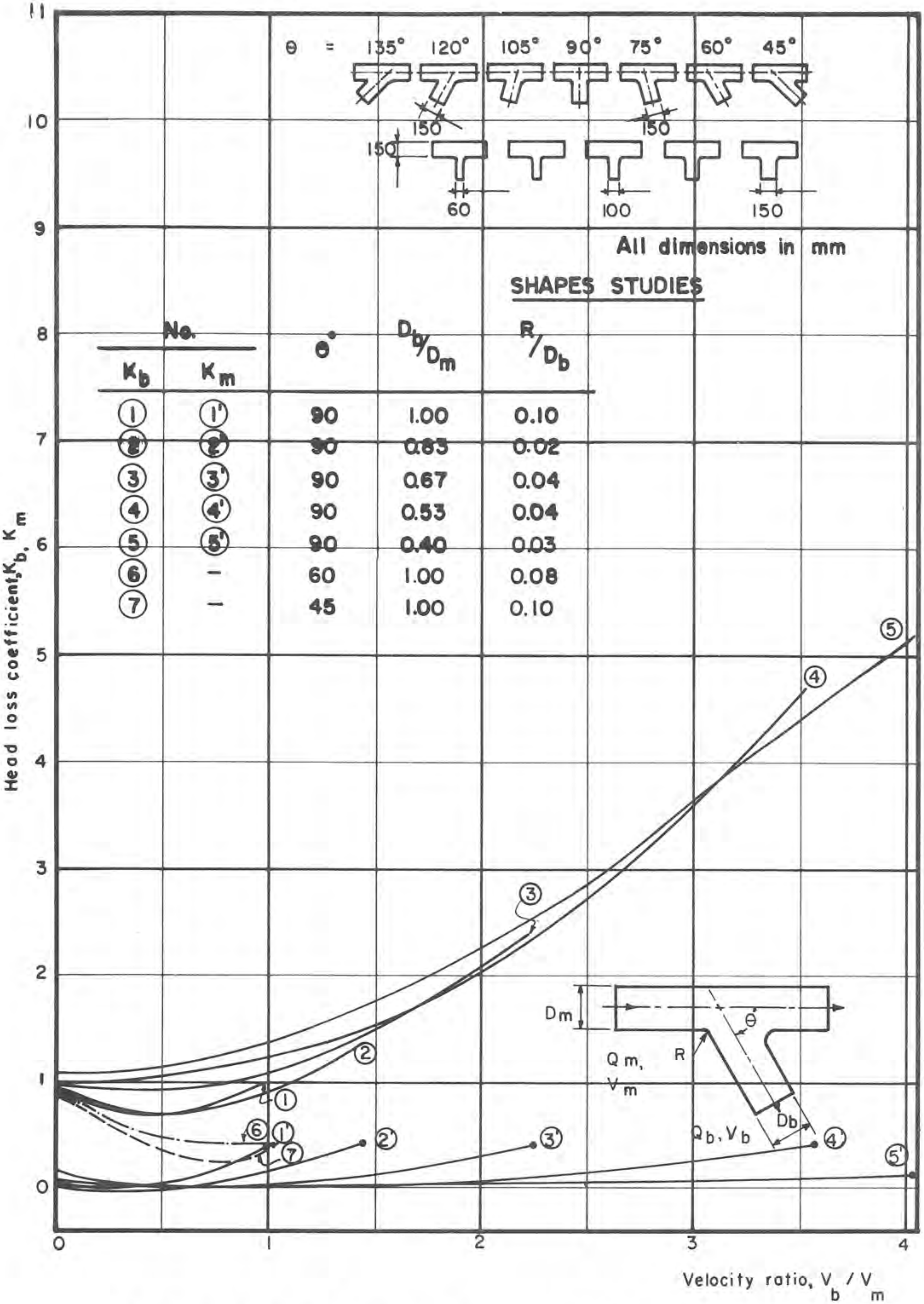


FIG.5. – GARDEL– CYLINDRICAL, ROUND EDGES

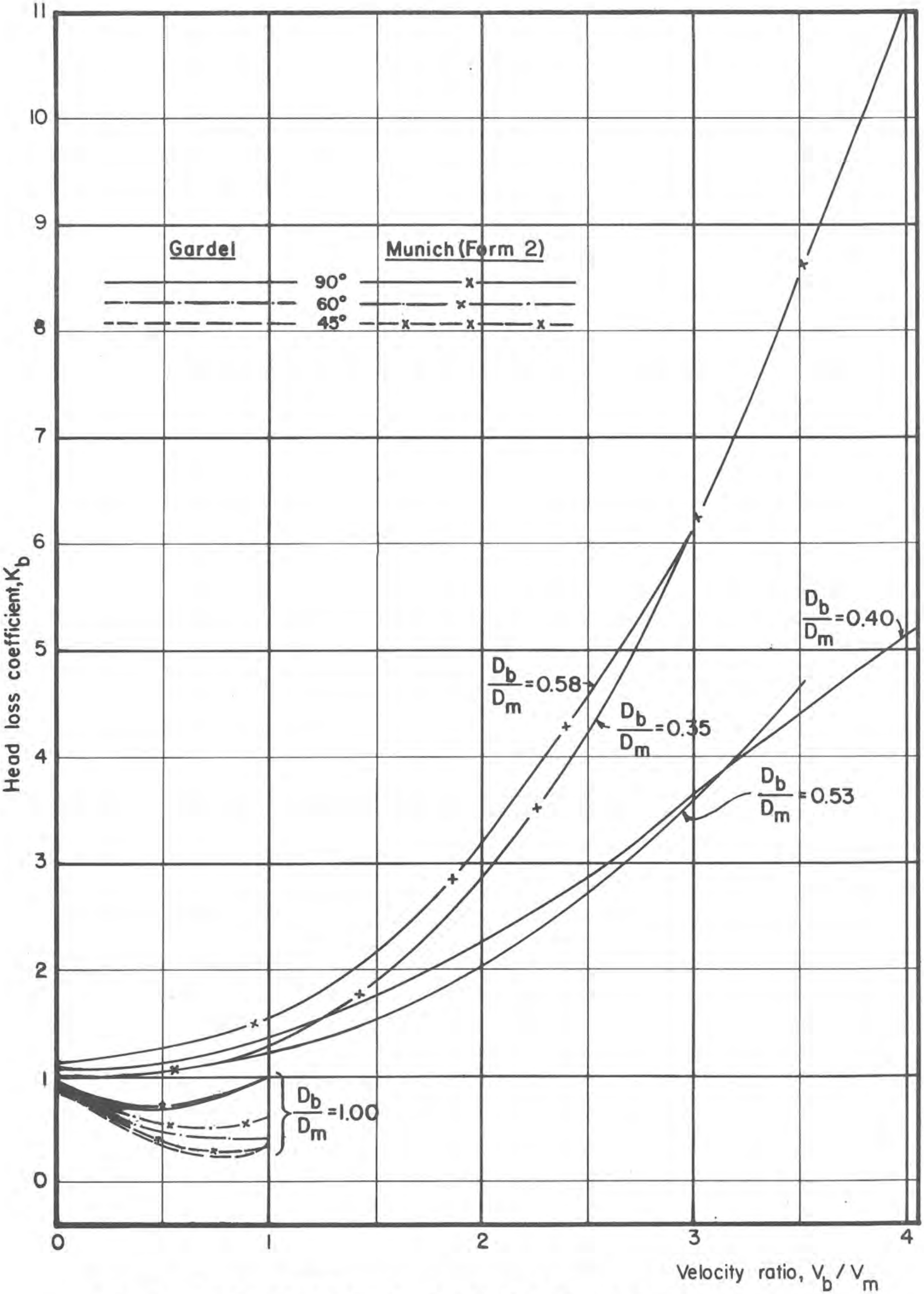


FIG. 6. – COMPARISON OF MUNICH AND GARDEL

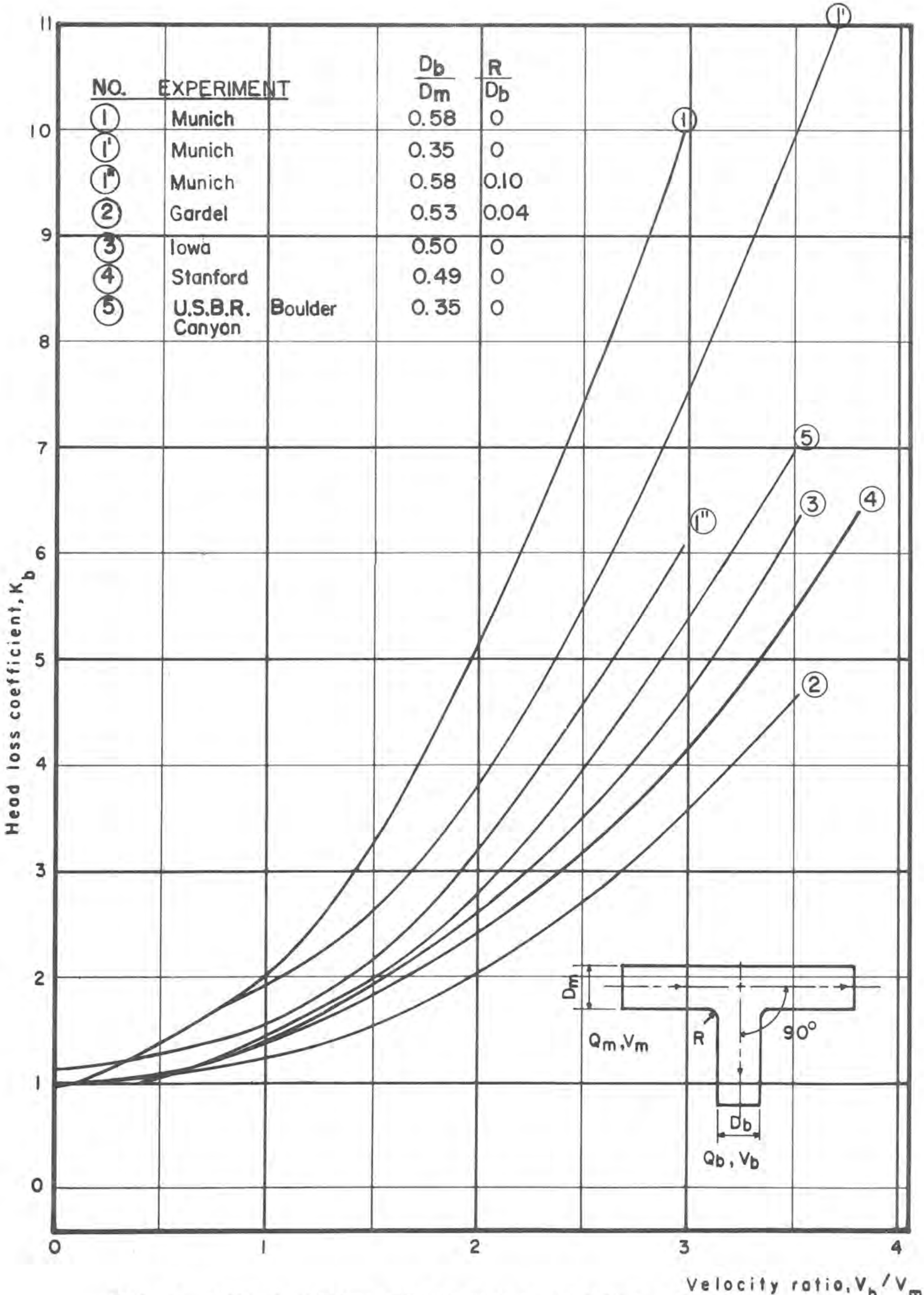


FIG. 7.– COMPARISON OF MUNICH, GARDEL, IOWA, STANFORD, AND BOULDER CANYON

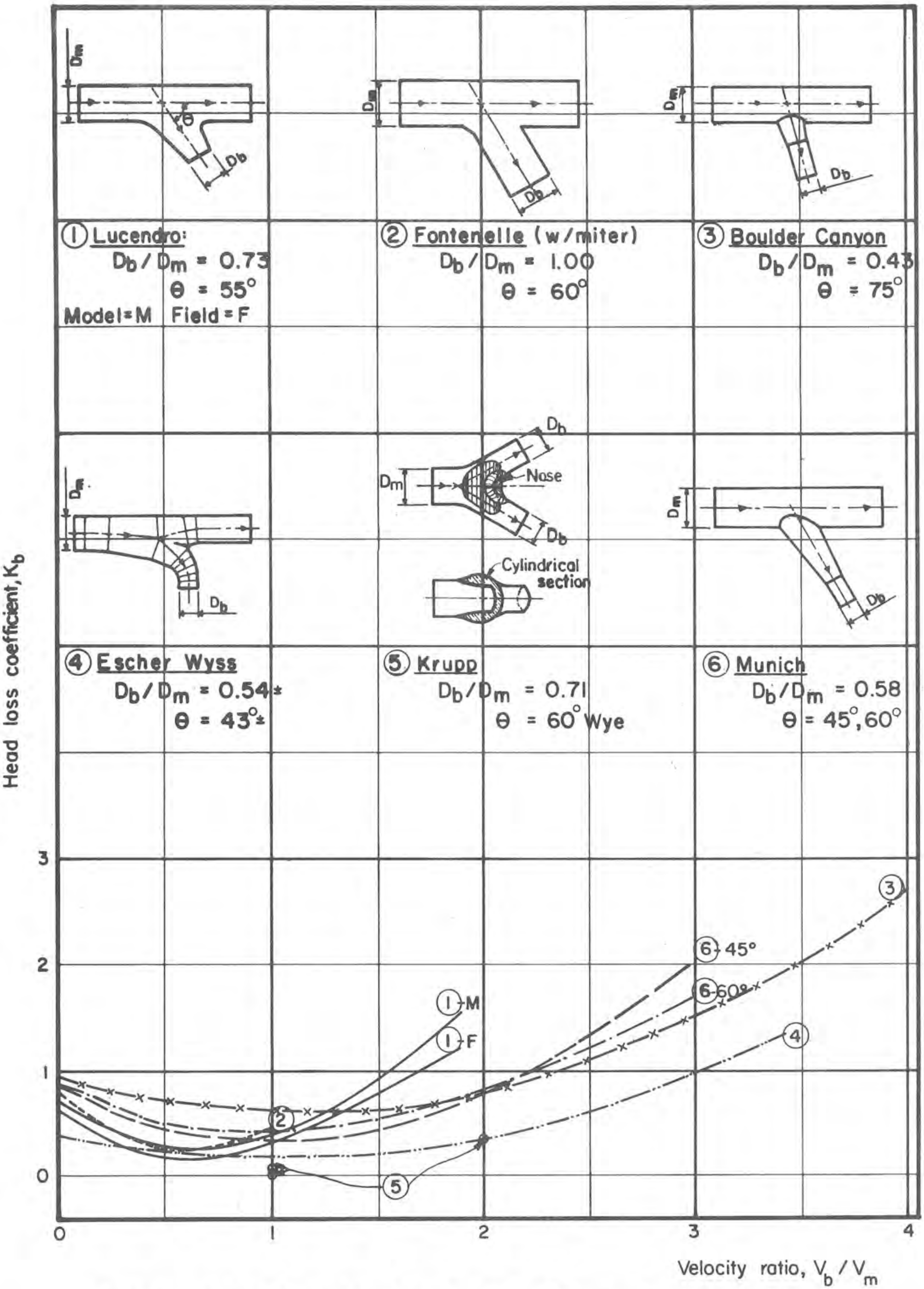
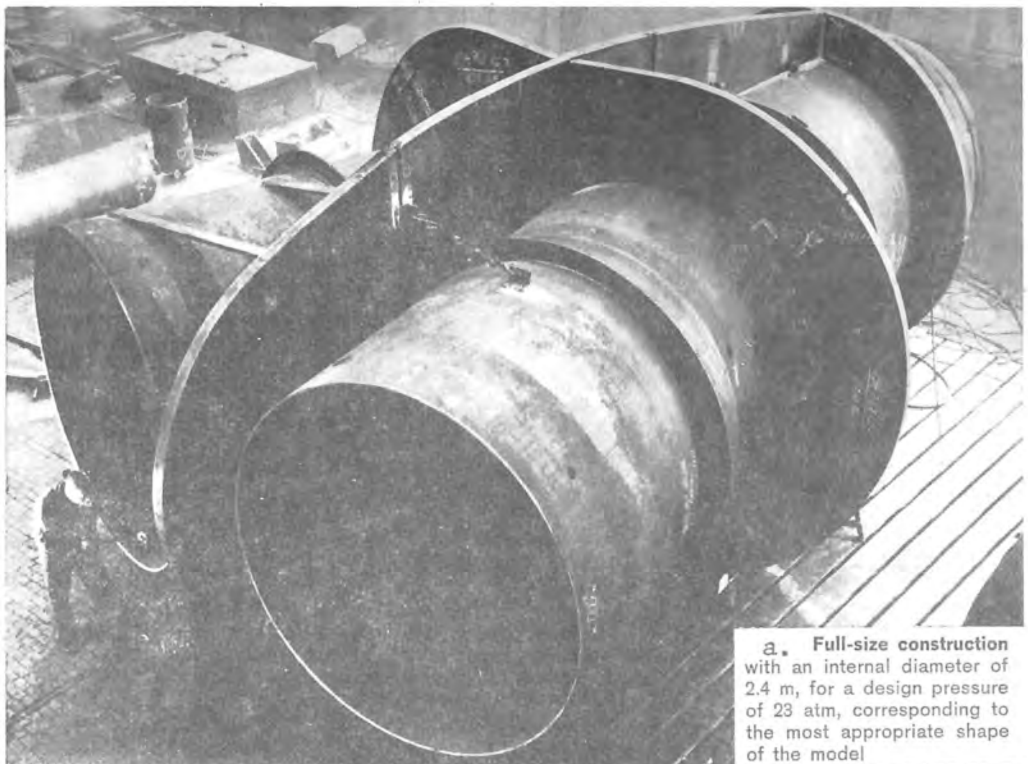
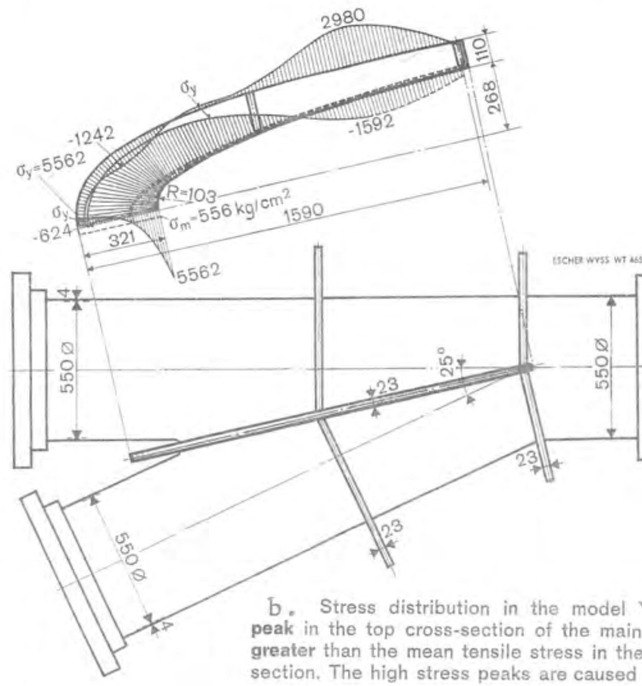


FIG. 8.- COMPARISON OF TESTS FOR LARGE CONDUITS

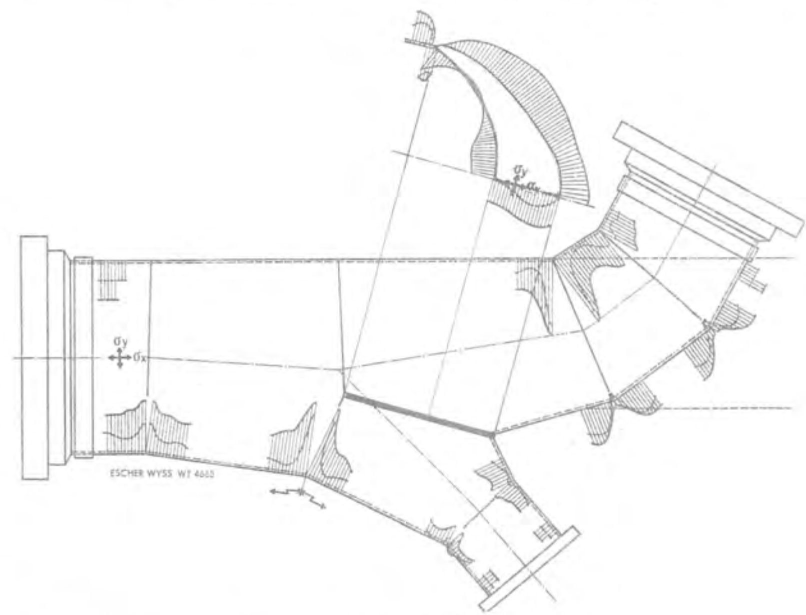


a. **Full-size construction** with an internal diameter of 2.4 m, for a design pressure of 23 atm, corresponding to the most appropriate shape of the model



b. Stress distribution in the model Y-pipe. The **stress peak** in the top cross-section of the main reinforcing rib **is 10 times greater** than the mean tensile stress in the corresponding pipe cross-section. The high stress peaks are caused **by bending**.

c. Branch pipe **with internally situated reinforcing rib** (Escher Wyss patent), for the Sils Manifold. Inside diameter at inlet 3400 mm; design pressure 48 atm; material: T_1.



d. **Measured stresses** on the experimental model of the Sils manifold.

FIG. 9– DEVELOPMENT OF ESCHER WYSS BRANCH

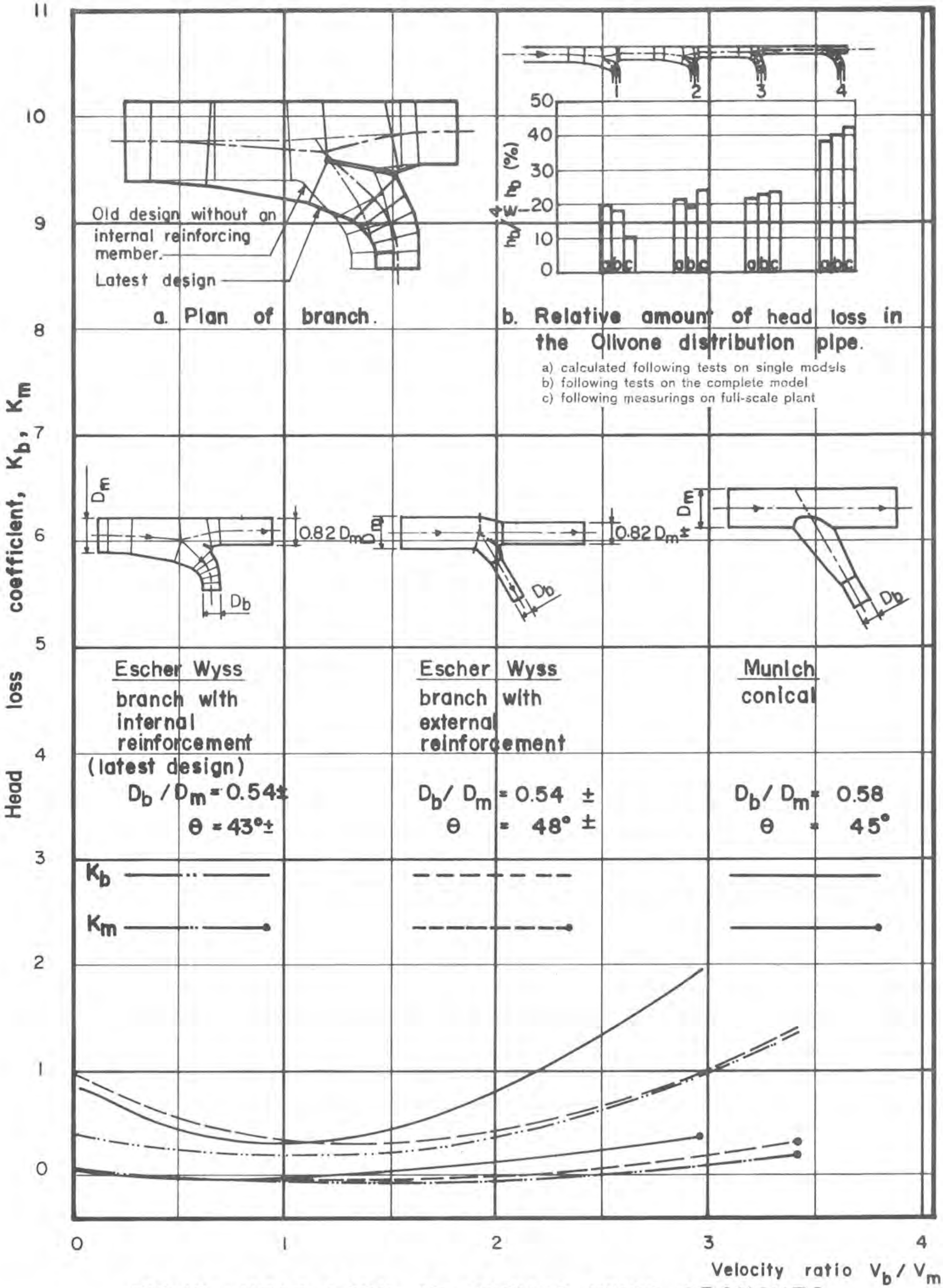
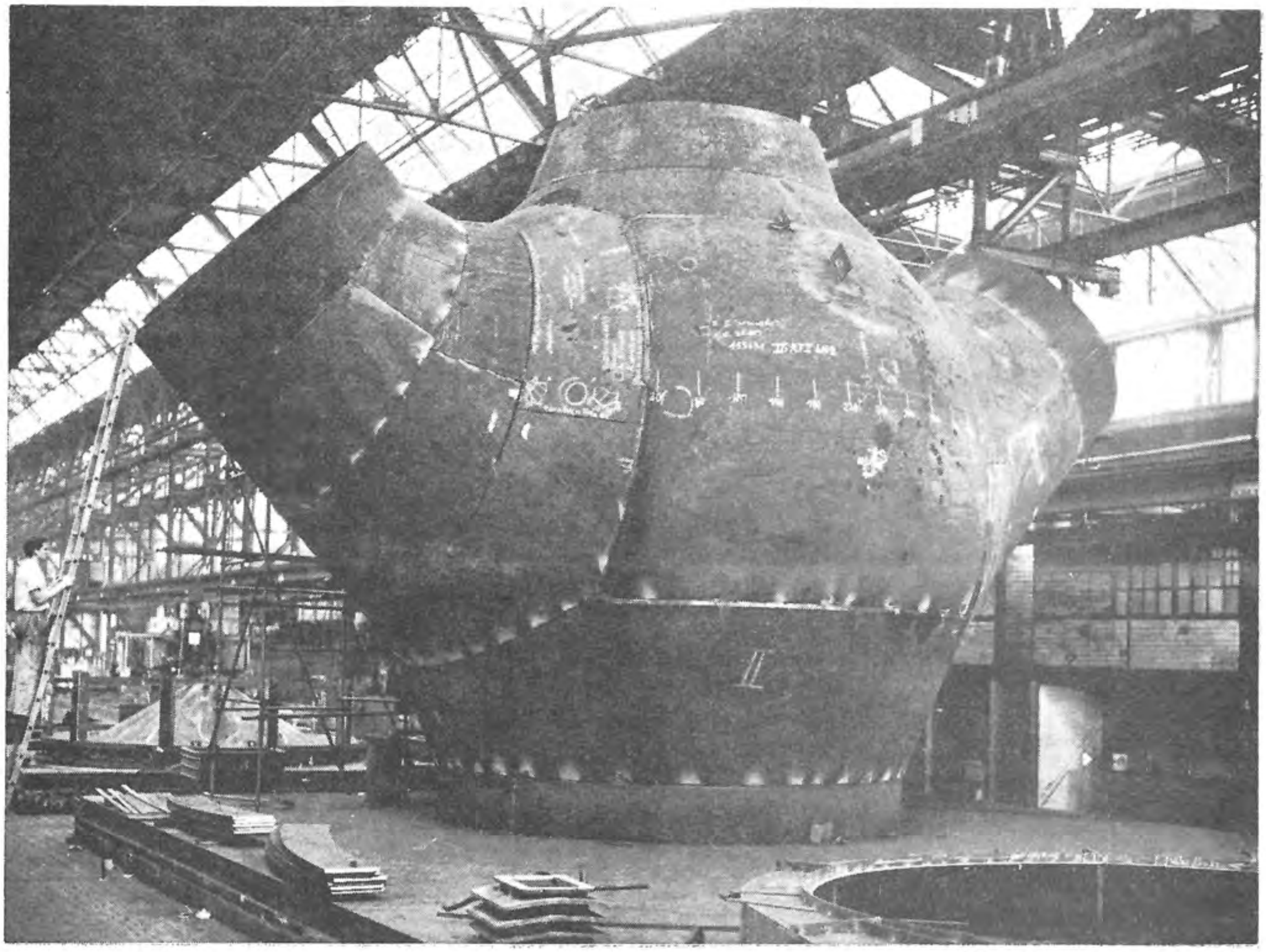
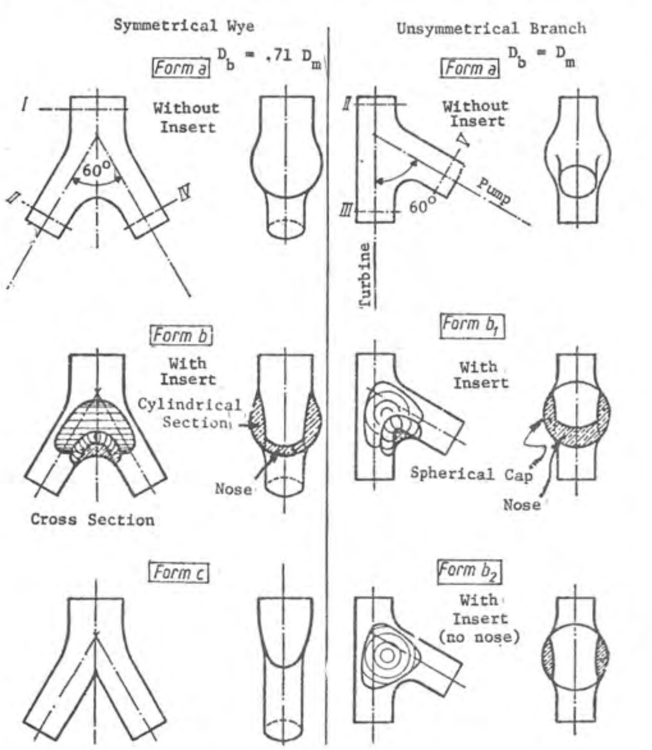


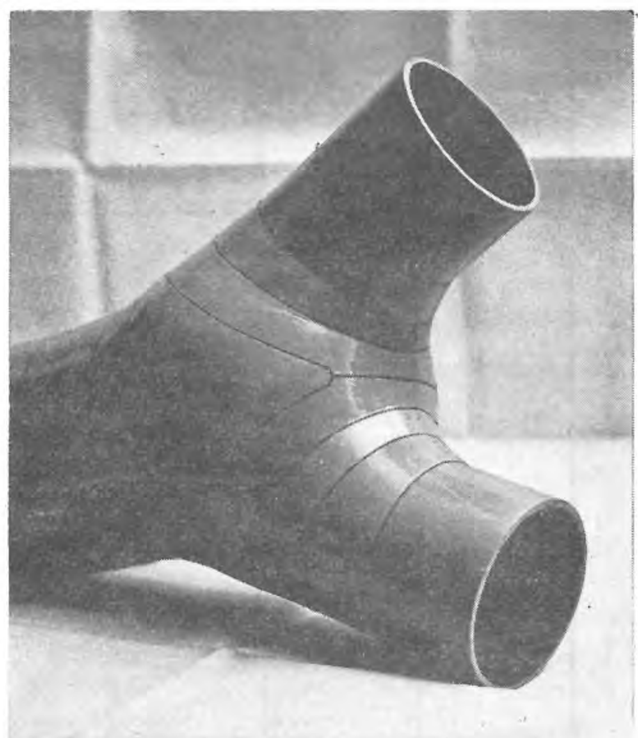
FIG. 10.– HEAD LOSS AT ESCHER WYSS BRANCHES



a. Fabricating a trifurcation of 7500mm sphere diameter by the new method



c. Model shapes tested



b. Model of a symmetrical 'Y'-pipe showing components

FIG. 11. – KRUPP BRANCH

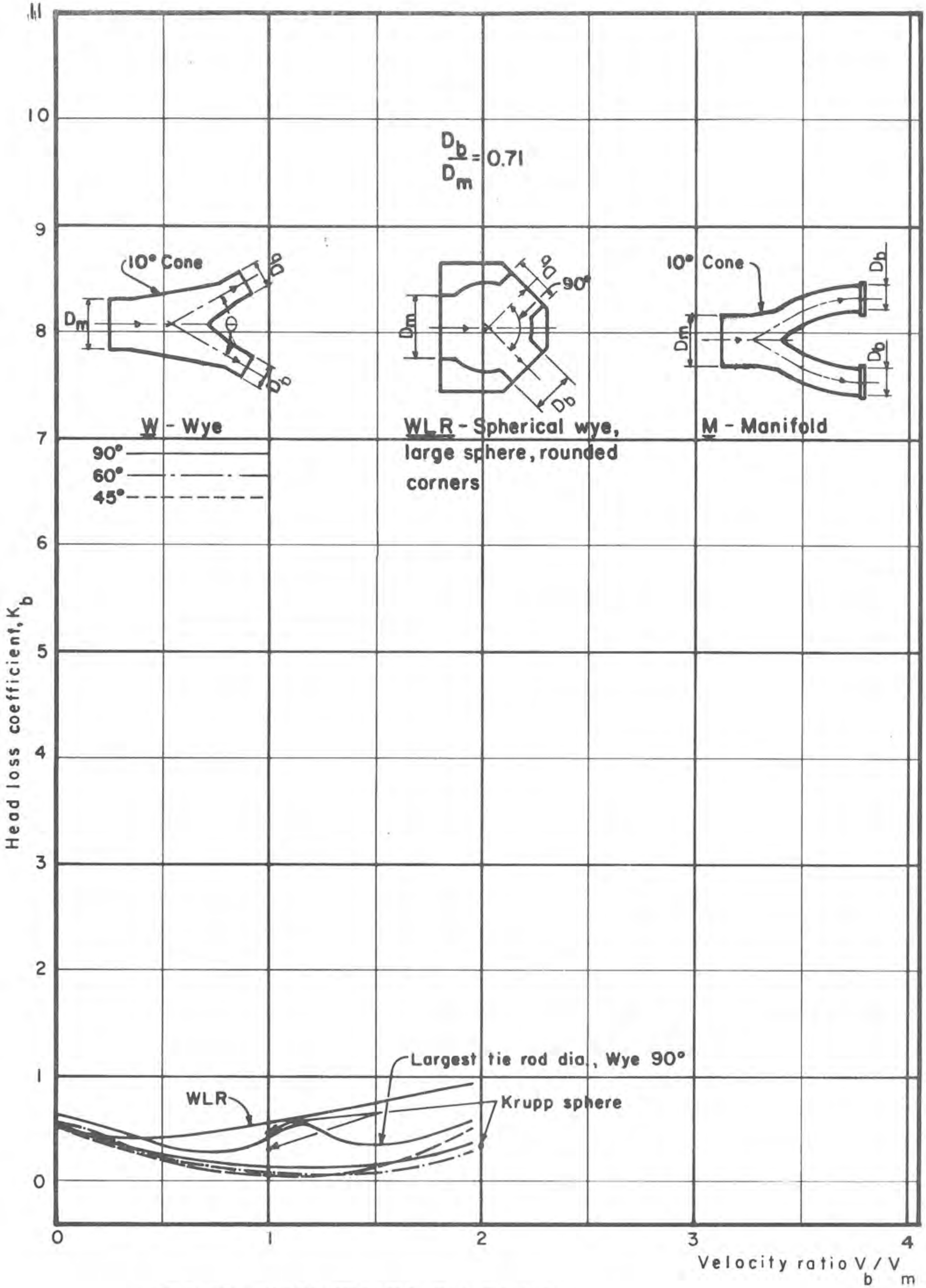


FIG. 12.– WYE TESTS BY RUUS

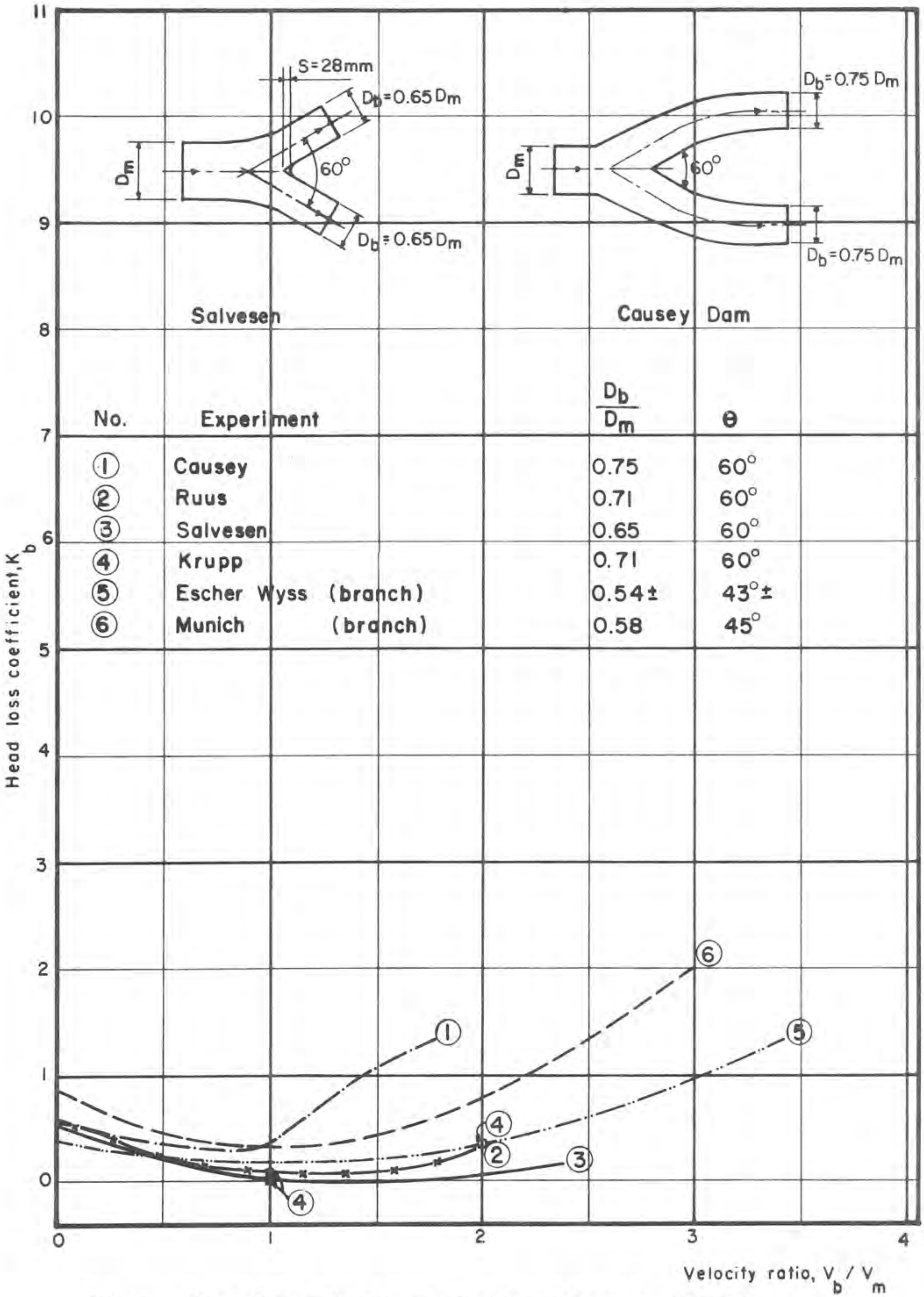


FIG. 13.– COMPARISON OF WYE AND BRANCH TESTS