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NORTH SEA FLOW METERING
WORKSHOP

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Gas Metering at High Reynolds Number

Lecturer: Joseph A. Bonner (M.Sc.)
Robsa Int., Belgium

GAS METERING AT HIGH REYNOLDS NUMBER

Joseph A. Bonner
Director of Engineering
INSTROMET GROUP COMPANIES

N.V. ROBSA INTERNATIONAL SA
2190 Essen - Belgium

Reynolds Number is the ratio of the inertial forces to the viscous forces in a flow system. Dynamic similiarity between two systems requires that all force relations in one system are equal to the force relations in another system. For many flow measurement applications, the only important forces are the inertial and viscous forces therefore an equal Reynolds Number in two systems is sufficient criteria for dynamic similiarity. The magnitude of the Reynolds Number indicates whether the flow is laminar or turbulent and also provides an indication of the probable shape of the velocity profile.

The Reynolds Number is a dimensionless ratio related to fluid viscosity, fluid density, the average fluid velocity, and the boundary conditions. For closed conduits that are full the Reynolds Number is

$$R = \frac{\bar{V} \ D \ \rho}{\mu}$$

Where $\bar{V}$ = the average fluid velocity

D = the pipe internal diameter

ρ = the fluid density

μ = the fluid dynamic viscosity

Even though the viscosity of gases is very low as compared to most liquids, the effects of the viscosity of gases plays an important rule in determining the velocity profile of the flowing stream. If there were no viscosity, the velocity profile of a flowing fluid would be uniform across the pipe cross-section. However, viscosity is a measure of a fluid's internal resistance to shear stress and even a small amount induces a shearing action between fluid particles that reduces the fluid velocity to zero at the pipe wall and thus creates a non-uniform velocity profile. Pipe roughness also influences profile.

Since the viscosity of gases is low as compared to liquids, it is normal to encounter high Reynolds Numbers in gas flow measurement. Typically the Reynolds Number is related to the pipe internal diameter and referred to as the pipe Reynolds Number. There are other boundary conditions that can be considered such as the throat of a venturi, the bore of an orifice plate, or the blading passage of a turbine meter rotor. Although comparisons of a general character are not too useful, the differences in pipe Reynolds Number for a 150 mm squared edged orifice meter operating at the same differential pressure on natural gas at 20 bar and a typical fuel oil with the same bore would be about 150 to 1. The gas flow would produce a Reynolds Number of about 3,000,000 while the oil flow would be in the 20,000 range.

The flow profile can be altered by pipe fittings which turn the fluid, expand or contract the stream, and any other item which is used in a typical piping system. Flow measurement is always assumed to have a fully developed flow profile and steady flow. If there are disturbances which create swirl or a distorted profile, these characteristics should be removed before measurement. At high Reynolds Number the inertial forces are high compared to the viscous forces and thus any disturbance will require a longer distance for the viscous forces to restore a normal profile than for a low Reynolds Number flow. These distances can be considerable and the usual practice is to install flow conditioners to force the profile to return toward normal in shorter distances. The effects of the distortion on measurement is also dependent on the type of measurement device used. Some meters are far less sensitive to profile distortion and swirl as compared to others.

Gas measurement at high Reynolds Numbers is prodominately done with square edged orifice plates and gas turbine meters. There are a few applications using other devices. Perhaps the question of "what is high" should be addressed. Most authors have settled on a Reynolds Number of 1,000,000. It seems like a reasonable figure when some typical installations are considered and also the data base for the coefficients of discharge for orifice meters.

The discharge coefficient for a squared edged orifice meter is correlated to Reynolds Number. Many tests were carried out with water and other liquids as well as gaseous. This data from different fluids could be correlated with Reynolds Number and therefore a discharge coefficient found on one fluid would be the same as found with another fluid providing the Reynolds Number was equal. In the calculation of the discharge coefficients from ISO 5167 "Measurement of fluid flow by means of Orifice plates, Nozzles, and Venturi tubes inserted in circular counduits running full" , the Reynolds Number term is

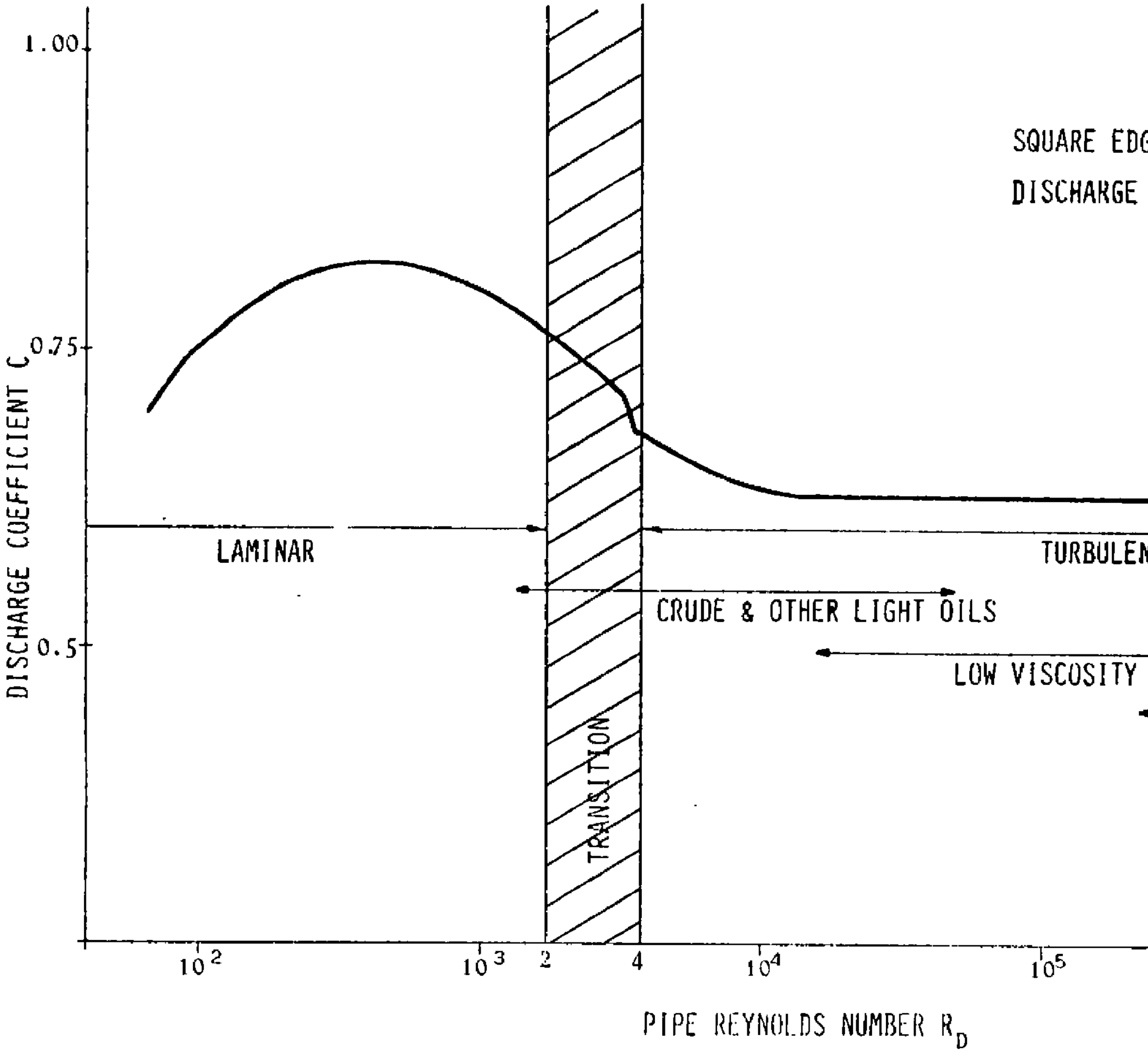
$$0.0029 \, \beta^{2.5} \left[\frac{10^6}{R_D} \right]^{0.75}$$

Where β = the ratio of the orifice bore diameter to the meter tube internal diameter.

Consider the differences in the Reynolds Number for the conditions below and the influence of this term in the discharge coefficient.

	R_D	10^4	10^5	10^6	10^7
β =	0.2	2.93×10^{-5}	5.22×10^{-6}	9.28×10^{-7}	1.65×10^{-7}
	0.5	2.87×10^{-3}	5.10×10^{-4}	9.06×10^{-5}	1.61×10^{-5}
	0.7	1.54×10^{-2}	2.74×10^{-3}	4.87×10^{-4}	8.67×10^{-5}

The change in the value of the term for low Beta numbers is on the order of 100 and high Beta by 1000. Since the prime term in the discharge coefficient is a constant of 0.5959 anything beyond 10^4 is meaningless and the values at 10^7 R_D indicate the fact the discharge coefficient stabilizes at a single value for higher Reynolds Numbers. Figure No. 1 shows a generalized plot of the discharge coefficient for the square edged orifice with Reynolds Number as the base. From observation of the equation for the discharge coefficient and the table above it will be noted that Beta has a strong influence. As indicated previously, a great amount of gas measurement is done at high Reynolds Numbers. There are installations operating at pipe Reynolds Numbers of 28,000,000 and perhaps others are higher but that is the highest of which I am knowledgeable. ISO 5167 limits the Reynolds Number for orifice plates at 10^8.


SQUARE EDG
DISCHARGE
DISCHARGE COEFFICIENT C
1.00
0.75
0.5
LAMINAR
TRANSITION
TURBULEN
CRUDE & OTHER LIGHT OILS
LOW VISCOSITY
10 2
10 3
2
4
10 4
10 5
PIPE REYNOLDS NUMBER R D

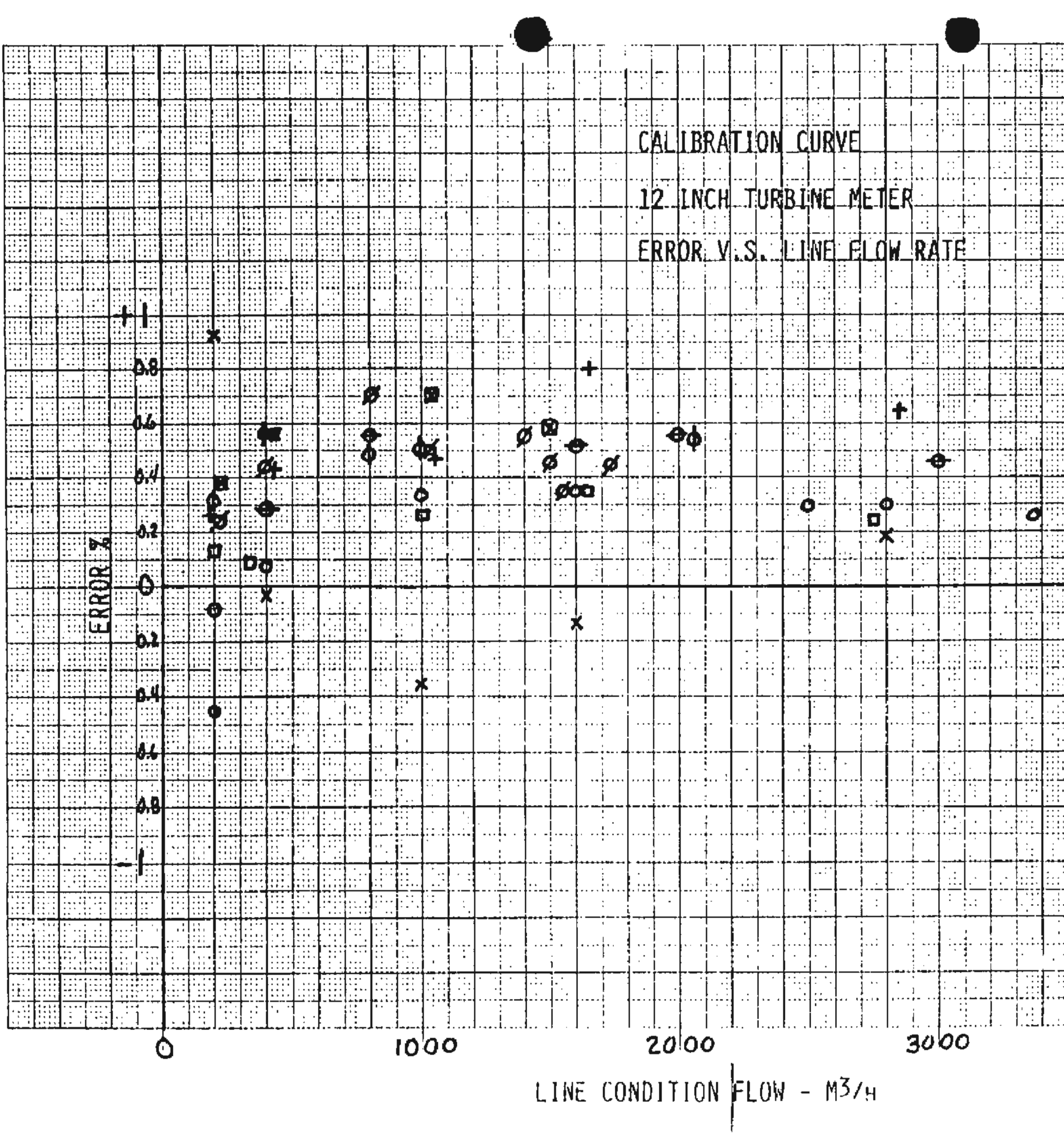
Presently, there is considerable research concerning orifice meter measurement. There is a 10 inch tube being used in a series of tests at various laboratories within the EEC. Some tests are completed however the results have not been published at this time. A series of tests covering tube sizes from 2 inch to 10 inch are being carried out in a research project sponsored by the American Petroleum Institute with assistance from the Gas Processors Association. The work is multi-phase and will take several years to complete. The present discharge coefficients are derived from the Ohio State water calibrations done in the 30's. There have been a number of research projects since then but the efforts were to confirm or extend the original data. Considering the differences in equipment capability between now and when the calibrations were carried out indicates that considerably more data can be collected and analyzed much quicker. Water calibrations will be carried out by the National Bureau of Standards at their Gaithersburg facilities. Gaseous calibration using nitrogen have been carried out at the N.B.S. facility at Boulder Colorado on some of the tube sizes. Much of the Boulder data has been published and one of the objectives was to test for the expansion factor used in gas measurement. Additional calibration work is planned for some of the tubes using natural gas which will allow much higher Reynolds Numbers and thus provide additional support for the extrapolation of the discharge coefficients for higher Reynolds Numbers. Tests for disturbance effects due to piping are also planned and some have started. Like all test programs there will be unexpected results or data which appears out of place. Good gas measurement is difficult and trying to reduce uncertainty in measurements is a continuing problem. There are many observers to all this activity and it is hoped that the activities of all experimenters will be considered. As a final note to all the square edge orifice meter work, it must be considered that most of these activities are under competent supervision and with many observers to question and comment. The results are to support or provide the basis for changing discharge coefficients and recommendations for use of the device. The control of a laboratory is far different from the practical use of the device in a true field operation environment. Regardless of the results and a hopeful reduction in uncertainty, the practical measurement will still depend on the continued attention by measurement technicians of the device they are using, its physical condition, and the accessories used to obtain the information required. There are many excellent installations that are poorly maintained with operators insisting that their measurement is excellent.

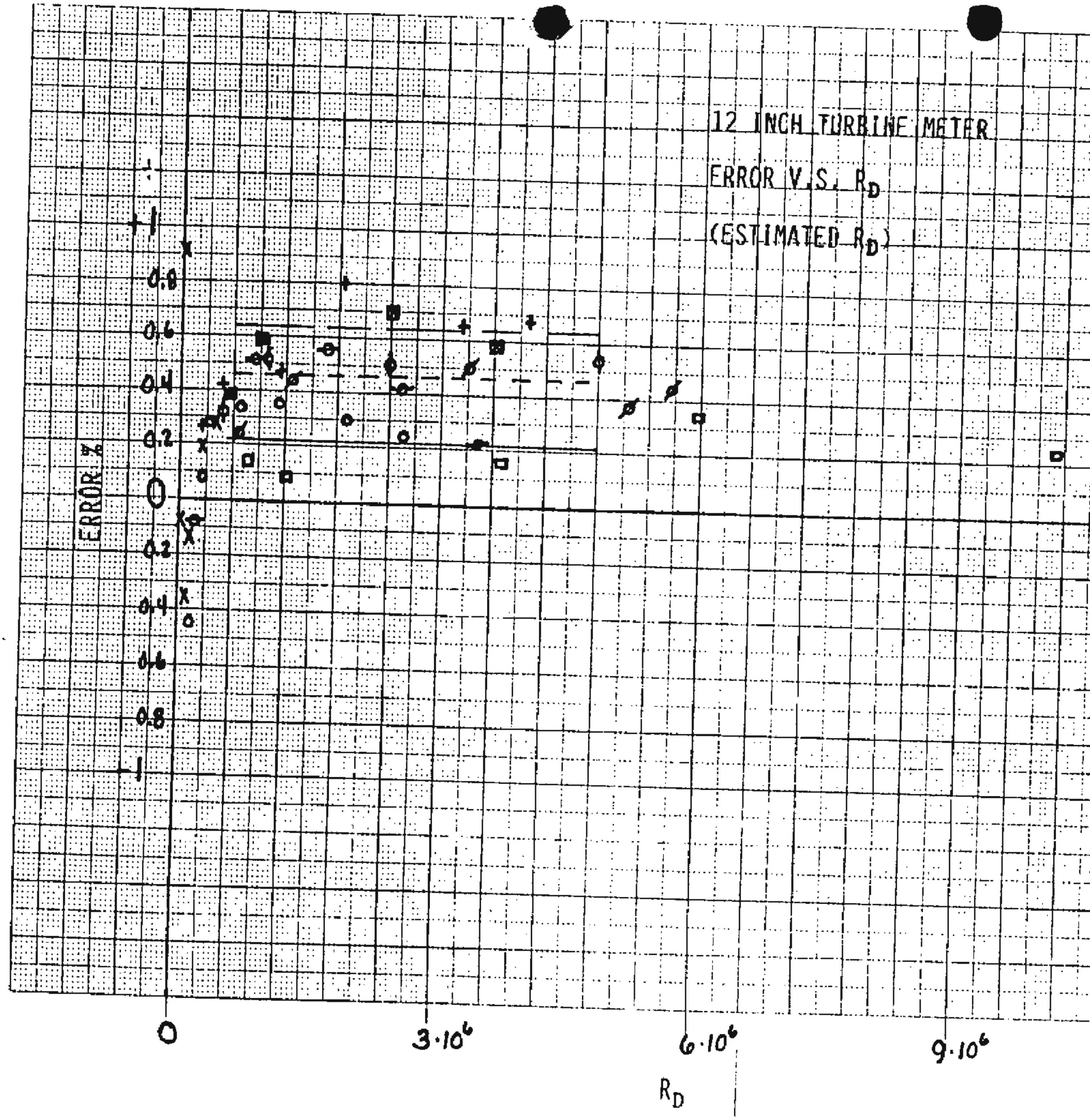
The other device commonly used to measure gas at high Reynolds Numbers is the turbine meter. Unlike the orifice meter which can have a discharge coefficient calculated from physical measurements, the turbine meter requires an individual calibration. There has been considerable change in turbine meter designs over the years and they are becoming more predictable but not to the degree required for sample calibration and not full calibration. A major difference in the turbine meter and orifice meter is that the turbine meter does not use the velocity profile of the pipe but tries to condition the stream and force a profile at the entrance to the rotor blading. Further, the rotation of the rotor tends to average out distortions since a higher velocity on a section will tend to increase the rotor speed and the lower velocity sector is given a semi-pumping action. Profiles are less important but they must be considered. Swirl, of course, does affect the meter performance in that the standard condition for the flow profile is axial without tangential components. Depending on the direction of the swirl the meter may speed up (over register) or slow down (under register). Small angles of swirl have little effect due to the inlet conditioning but large angles can cause significant changes.

An interesting method of plotting turbine meter performance is to plot the error of the meter against Reynolds Number. The plot should produce a single curve to define the meter performance except for the lower kinetic energy levels where friction and other influences predominate to affect the performance. This does not mean the error curve will be a straight line, it means it should plot a continuous curve and a calibration done on one fluid can be compared to data obtained on another fluid or different operating conditions. Of course, there are some meters which will not make a smooth plot. Generally, there is a valid reason for this and other effects should be suspected if a smooth plot does not exist. Some of the early designs would not plot against Reynolds Number and produce a continuous curve. There were reasons that explain this behavior. In some of these meters the blading would bend due to the pressure differential and this would change the angle of the blading and produce some rather interesting results. The fact that the data would not plot a smooth curve of error versus Reynolds Number was sufficient to become suspicious that something was occurring that was unknown. There are other examples where design problems could be detected by the resulting test data. There are many examples of problems in the mechanical design that were revealed by careful analysis of the data and the most powerful tool was a plot based on Reynolds Number since that related to density and viscosity effects while other data plots would ignore one or the other. The ability to plot an error curve against Reynolds Number requires the access to test facilities that can produce a wide range of Reynolds Numbers in the testing. Unfortunately, in the early years of the development of the turbine meter for gas service, test facilities were not readily available and were severely limited in capacity. Today there are a number of test facilities with varying capabilities and so it may be necessary to use several to obtain a satisfactory data base.

Figure No. 2 shows a plot of a 12 inch turbine meter tested under a wide range of conditions. The data is from several laboratories and includes data obtained on low pressure air. Initially, it may appear there is considerable deviation in the data. There are some questionable points however they can be analyzed if the data is generalized - such as a Reynolds Number plot. In Figure No. 3 the data is replotted with an estimated Reynolds Number. It becomes obvious that there is some bias between laboratory facilities. That does not say which is right or closer to the truth but that there is some bias. If you don't allow individual points to blind you, there is a generalized smooth curve for the data and if the apparent bias of the laboratories is removed the data forms a smooth curve over a significant range of Reynolds Number. The other differences that exist require considerable more analysis of the data which is not a task intended in this paper.

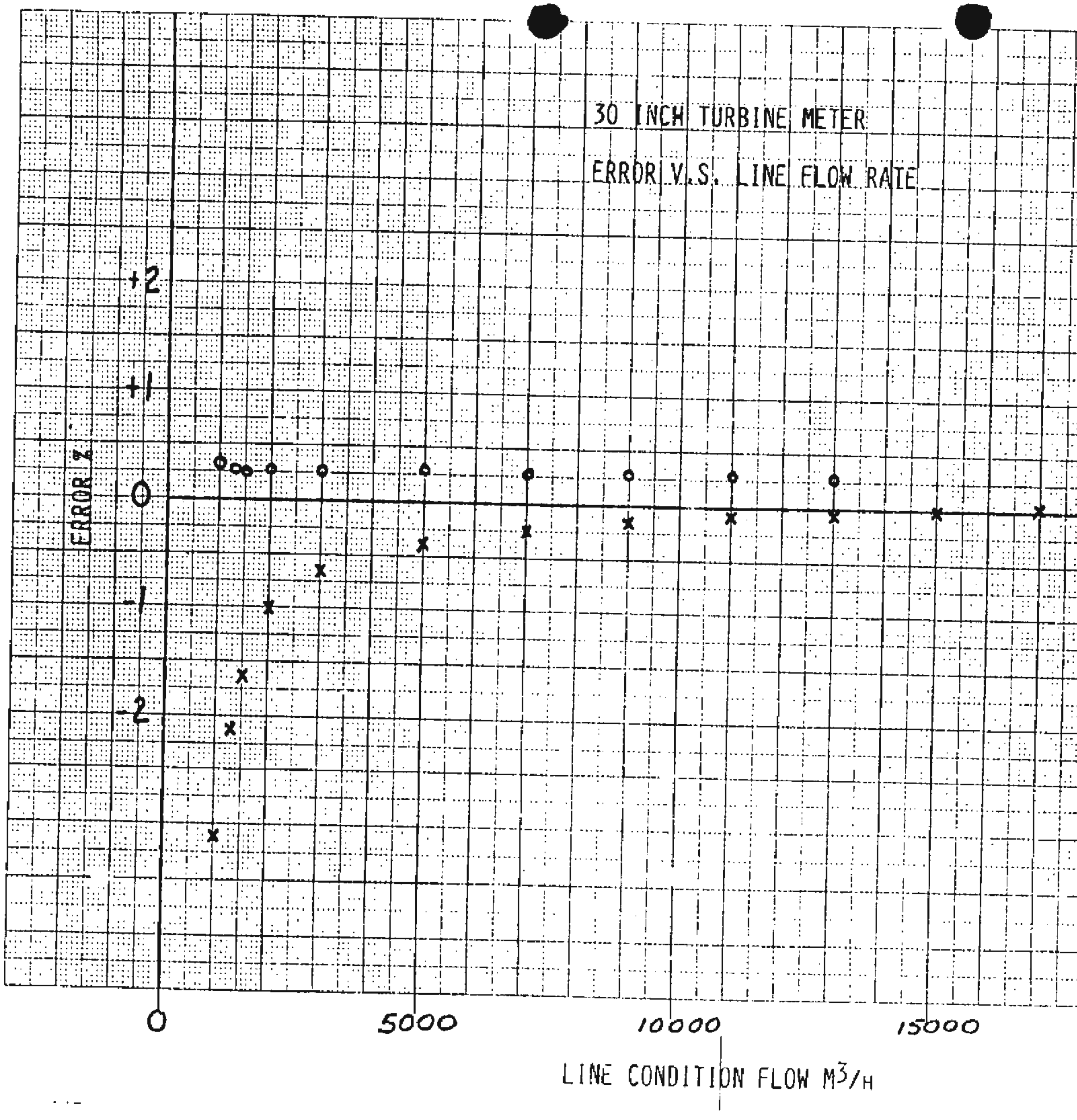
Another meter, a 30 inch in size, is shown in Figure No. 4. This data is plotted in the traditional way. The same data plotted on the estimated pipe Reynolds Number does not yield much information because there is a gap between the air data and gas data and no means of determining if it is the differences in the references or that the meter does truly display a slight shift between a R_D of 800.000 and 1.500.000. My personal opinion is there is a difference in the references and regardless of the difference it is extremely small. As noted before, a turbine meter requires an individual calibration and most are done with air at atmospheric conditions. If this air calibration is performed, then what might be expected under operating conditions considerably different. That in itself is rather complicated, however, if a portion of the curve at a higher pressure can be established the prediction becomes much easier for meters that are well designed for higher operating densities. There should be some points which relate on a Reynolds Number basis or on a base rate basis (there


CALIBRATION CURVE
12 INCH TURBINE METER
ERROR V.S. LINE FLOW RATE
+1
0.8
0.6
0.4
0.2
0
0.2
0.4
0.6
0.8
-1
ERROR %
0
1000
2000
3000
LINE CONDITION FLOW - M3/H


12 INCH TURBINE METER

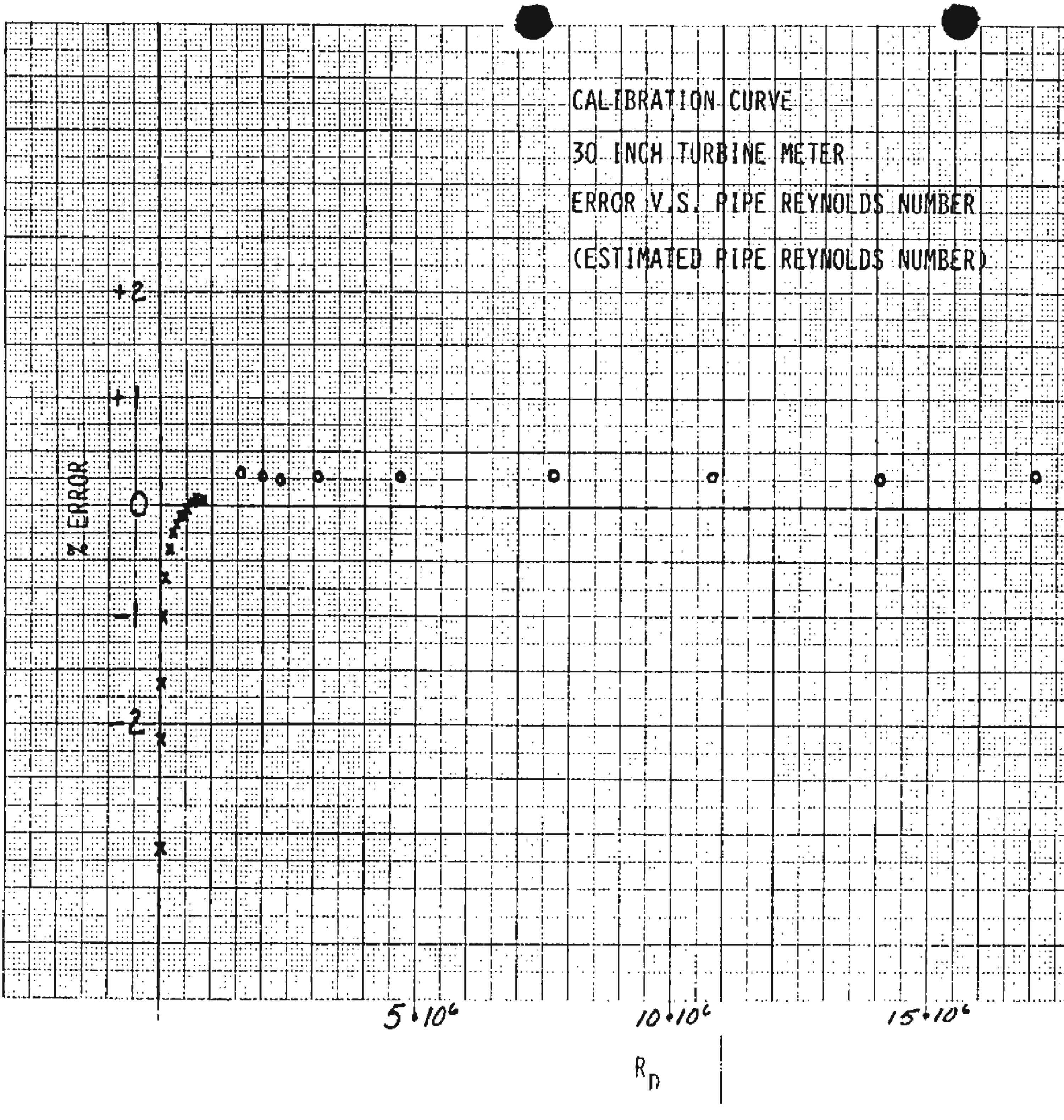
ERROR V.S. R_D

(ESTIMATED R_D)



30 INCH TURBINE METER

ERROR V.S. LINE FLOW RATE


CALIBRATION CURVE
30 INCH TURBINE METER
ERROR V.S. PIPE REYNOLDS NUMBER
(ESTIMATED PIPE REYNOLDS NUMBER)
+2
+1
0
-1
-2
% ERROR
5•10⁶
10•10⁶
15•10⁶
R_D

is a reasonable relationship between the two). A coupling of the curves indicates there is not something unusual in the performance. The remaining judgement is to determine if the curve is rising or falling or flat. If the latter then the meter will probably remain flat under a wide set of operating conditions. If the curve is rising or falling there will be some shift and then only a considerable background with similiar data will give an indication of how much shift can be expected.

There have been a large number of meters calibrated at higher operating densities. In fact, some gas turbine meters have been calibrated with liquids to move the density to very high values although the Reynolds Numbers were very low. The correlation of the data was quite good. Some of these meters are operating at Reynolds Numbers above 10^7 and some into the 2×10^7 region. There are considerably more meters operating in the 10^6 to 10^7 range. Metering at high Reynolds Numbers on gas systems is rather commonplace. Many of these meters are calibrated at higher densities and it appears that more calibrations at higher densities will be carried out in the future. Depending on the degree of confidence one requires, a calibration at 7 to 8 bar will yield considerable data for projections to higher density. Meter manufacturers are working to control the turbine meter performance over a wide range of densities however it will still be necessary to calibrate. The time when a meter can be tested on low pressure air and expect the same results under high densities is not at hand but it is getting closer.

As a final note, all gas metering requires attention to the equipment maintenance and to the actual installation in the design stage. Ideally, we want a meter that can be installed in any piping configuration, operates over a wide range of conditions, requires no maintenance or attention, and produces perfect results. I was once told that such existed - a meter with one of its block values closed - since then I have found that that does not produce perfect results and sometimes very incredible results. Good gas metering requires work.

References

[1] Paper presented at the North Sea Flow Measurement Workshop, a workshop arranged by NFOGM & TUV-NEL

Note that this reference was not part of the original paper, but has been added subsequently to make the paper searchable in Google Scholar.