NIST's Ultrasonic Technology Assessment Program to Improve Flow Measurements

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Summary:
This report presents results of the first phase of a three-phase effort conducted at NIST to assess ultrasonic technology for improving flow measurement. Each of the three phases is planned to contain results from: (a) testing commercially available, travel-time, clamp-on type ultrasonic flow meters, (b) modeling the pipe flows involved, and (c) producing computer simulations for wide variations of the arrangements of these meters. Meter test results were done using water in 250 mm diameter, stainless steel pipe where the Reynolds number ranged from 4E5 to 3E6. These tests were done in meter installation conditions considered ideal where pipe flows were measured using laser Doppler velocimetry (LDV) along horizontal and vertical diameters and found to be satisfactory approximations to ideal conditions. LDV results include mean velocities and turbulence components in the axial and transverse directions.

The first phase test results show that most of meters tested had errors in the range from 0% to 3%, relative to NIST's static gravimetric flow standards. The worst case error was –14%. Results also showed that these meter manufacturers have progressed well in correcting historical problem areas associated with "remove-replace" variations and with "zero-flow" set-up requirements in order to attain specified performance.

The flow modeling results indicate that for the conditions tested, very long lengths of constant diameter piping are required to produce ideal, fully developed flow conditions. The computer simulations of ultrasonic metering techniques indicate the consequences of the software strategies used to process final results and they indicate the trends in performance as flow conditions vary. These simulations indicate that, while the manufacturers of the tested meters are compensating for pipe flow distributions, the compensations are not sufficient, and the trends shown with flow rate are frequently opposite to that shown by the simulations.

As part of these tests, NIST put two, in-line flow meters, a magnetic type and a multipath ultrasonic type, in the test pipe to monitor the flow stability while standards were collecting water to determine the averaged flow rate result. Both of these records confirmed the temporal stability of the test conditions, and one of them, the multipath ultrasonic meter, included its diagnostic capabilities to assess and compensate for these pipe flow features to produce highly accurate flow rate measurements. For most of the flows tested, the uncertainties of this multipath ultrasonic meter were ±0.2% or less.

Based on the results of these first phase results, ultrasonic flow measurement technology has progressed well in recent times and ultrasonics can satisfy additional needs in flow measurement.

Introduction:

Technical advances in ultrasonics can significantly improve flow measurement in the continuous process industries. A description of ultrasonic metering can be found in [1]. Ultrasonic techniques have the potential to serve as replacement flow meters, to comprise high level transfer standards for calibrating other meters, and to conduct proficiency tests to compare laboratory uncertainties. Furthermore, as understanding of ultrasonic metering methods spreads through the flow metering community, these methods may evolve into primary flow standards. This potential exists for both liquid and gas flows; it also exists for wide ranges of pipe sizes and geometries, as well as for fluids with different compositions over wide ranges of temperatures and pressures. However, to realize these potentials, this technology needs to be thoroughly assessed.

NIST, in conjunction with several meter manufacturers, is assessing ultrasonic technology and assisting in advancing it to improve flow measurements. This technology, specifically the application of travel-time techniques to pipe flows using clamp-on sensors, has prospects to serve as transfer standards that can be scaled to calibrate other flow meters in larger pipes or higher flow conditions. Such a capability could greatly improve the performance of flow meters that have capacities too high to be directly calibrated in NIST's flow facilities or elsewhere. Furthermore, if one considers a primary flow standard to be one for which a satisfactory understanding exists so that a calibration isn't required for its result to be accepted at its quoted uncertainty, it seems feasible that travel-time ultrasonic techniques could become primary flow standards. This is because these techniques use simple length and time measurements to determine chordal or diametral averages of flow velocity in fully developed, equilibrated pipe flow to determine flow rate. These techniques also offer capabilities for diagnosing pipe flows by assessing swirl, cross-flow, and turbulence characteristics.

To assess currently available, ultrasonic technology for measuring liquid flow using clamp-on type, travel-time flow meters, NIST devised a program to quantify their characteristics in "ideal installation" conditions and in two, typical "non-ideal" conditions. An "ideal installation" is one where the pipe flow is the fully developed, equilibrated distribution such as that produced naturally by long straight lengths of constant diameter pipe or by special flow conditioners that interact with the pipe flow to produce profiles that closely approximate the naturally produced ideal flow. Typical "non-ideal" conditions are pipe flows downstream from a conventional elbow and the flow downstream from a reducer. Elbows and reducers are pipeline elements that are frequently found upstream of flow meters.

As part of the test program, NIST has extended its Computational Fluid Dynamics (CFD) flow modeling capabilities to the fluid and flow conditions planned for the test program. Results are used to understand not only the characteristics of the pipe flows developing ideal conditions, but also the complex flows downstream of the elbow and the reducer. In these computed flows, simulations of a number of arrangements of travel-time ultrasonic meters can be done to better understand how the meter's output depends on the arrangement and the interpreting software.

The three types of results from this phase of the program are:

1) the testing of the clamp-on, travel time units,
2) the CFD results for flow profile development in straight pipes, and
3) the computer simulations of travel-time techniques.

They are expected to benefit wide sectors of the flow measurement community – meter users, meter manufacturers, and those in the flow meter calibration laboratories interested in expanding their calibration capabilities. It seems that travel-time ultrasonic techniques could meet the needs of this last sector. If the results of these assessments can be successfully scaled up to larger pipe sizes and larger flow rates, etc., the improvements in flow measurement traceability should lead to satisfactory flow metrology for much wider ranges of fluids and flow conditions.

<u>The Meter Testing Program</u>:
NIST devised the testing program with assistance both from metrologists in the continuous process industries and from five ultrasonic meter manufacturers. All manufacturers of clamp-on type travel-time ultrasonic flow meters were invited to participate. The participating manufacturers and their respective meter models are listed alphabetically:

Advanced Measurement Analysis Group, (AMAG),…"a Cross Flow SCU-DIG-1996"
Ontario, Canada,

Controlotron, Inc.,…"a Model 1010 V1"
Hauppauge, NY,

Krohne,…"a UFM 600 P"
Peabody, MA,

Mesa Labs,…"a Micro Flow 90"
Lakewood, CO,

and

Panametrics, Inc.,…"a DF 868, with transducers: CPT-10-NT"
Waltham, MA.

The Cooperative Research and Development Agreement (CRADA) with these participants stipulates that the test data produced in this program will be presented anonymously. Each participant will be informed of the identity of his data only.

Each participating meter manufacturer was required to use the same unit throughout all 3-test phases. The first phase test objectives were to quantify the repeatability and the reproducibility of the participating units in a 2-day program of tests. See [2]. The NIST national standards for water flow measurement were used for these tests; these are described in [3]. Figure 1 shows a sketch of the test line used. Tests were done by clamping meters on the 1.8 m length of stainless steel pipe in the meter test section and testing these units using NIST 's primary gravimetric flow standards. To minimize the variation associated with the clamp-on installation, the manufacturers performed these tasks.

The range of Reynolds numbers covered for all participants was:

$$4E5 \leq Re \leq 3E6.$$

The pipe flow characteristics in the test pipe were measured using LDV [4] for the highest and lowest flows tested. Results are shown in Figure 2 along horizontal and vertical diameters traversing the test pipe just downstream of where the meters were installed. These results were achieved using the flow conditioning elements shown in the sketch in Figure 1 Figure 2 shows: (a.) relatively low levels of skewness of the axial mean velocity profile, (b.) small transverse velocities, and (c.) the expected distributions for the axial and transverse components of the turbulent intensity. Based on these results, the test conditions were considered satisfactory approximations to ideal, fully developed pipe flows. See [5,6].

The NIST flow standards use static gravimetric techniques to determine the flow rate with an expanded uncertainty of ± 0.12%. See [3]. These standards were used to assess meter indications that were averaged over the timed collection intervals. To obtain real-time data for the pipe flow in the test pipe during the 40 s to 140 s intervals during which the NIST static gravimetric standards operate, two different types of the flow meters were installed downstream of the meter test section. The first of these downstream meters is denoted by "U" in Figure 1. It was a Fisher Precision Systems, Inc. Model 2502[1] in-line or wetted sensor, ultrasonic flow meter having 8 chordal paths. The second of these downstream meters is denoted by "M". It was a Marsh-McBirney, Inc. Multi-Mag Model 284[1] insertion magnetic flow meter. This unit inserts an elliptical, diametral strut vertically through the test pipe. The major and minor axes of this strut were, respectively, 4.5 cm x 1.6 cm, with the major axis aligned with the flow direction. Both of these meters were installed in the test pipe just downstream of where the profile measurements shown in Figure 2 were obtained. Data recordings for both of these meters were made at 2 Hz through the intervals when the NIST gravimetric standards were used; the output of this magnetic meter had a time constant of several seconds. The recording rates ranged from 0.2 Hz to 1 Hz among the tested meters. The rates were selected by the manufacturers to give optimal performance.

The time averaged results for the participating meters and the in-line ultrasonic and magnetic flow meters were assessed using the timed collection values obtained using the NIST standards. The deviations of the rapidly recorded outputs from both the in-line ultrasonic and magnetic meters and from the participating meters were expressed as single standard deviations and graphed using error bars about mean values.

[1] Use of commercial names is only intended to be descriptive; it should not be considered an endorsement by NIST. The named product may not be the best product for the task at hand.

Further averaging was done to quantify repeatability and reproducibility for both the in-line and participating meters, as described below.
The first day of the 2-day test quantified participating meter performance without and then with a "zero flow" condition. To quantify the repeatability of the participating meters without a "zero flow" set-up condition, the initial installation of each participant's meter was done with flow in the test pipe. Once the meter was installed, a three flow test sequence was run in which five static gravimetric determinations of flow rate were done at each flow. Nominal Reynolds numbers for these flows were: 4E5, 1.6E6, and 2.9E6. Once the first sequence was completed, the flow was stopped. A second sequence was done without alteration of the meter.

Each of the five static gravimetric determinations of flow rate with NIST standards was compared with the average of the recorded participating meter results taken during the gravimetric collection. The difference between these results, expressed as a percent of the reference result was then averaged and the standard deviation of these five results, also expressed as a percent, was considered to be the meter repeatability for the pertinent test condition. After this test was replicated, the ten results at each flow were averaged and the standard deviation of these was considered to be the meter reproducibility for the condition. In what follows, these tests for the "non-zero" start condition will be referred to as T1 and T2. The designations T3 and T4 indicate the corresponding results for the "zero-flow" start condition. Figure 3 sketches the test sequence and the data for the first day of tests.

To quantify participating meter performance when the units are removed from the test pipe and then re-installed, tests were done on the following day in which the sensors were removed from and replaced on their "rails" or test fixtures, which remained attached to the test pipe. These tests are designated T5. Tests designated T6 were conducted in which both the sensors and rails were removed and replaced. These remove-replace tests were only done for the lowest and highest flow rates; at each of these, five replications of tests were done in rapid succession using NIST's gravimetric standard as the basis. Results were averaged and standard deviations were produced as presented using error bars for the tests designated T5 and T6. Figure 4 sketches the test sequence and the data for the second day of tests. Therefore, the data set for each participant includes 80 points: 30 each for the low flow (Re = 4E5) and the high flow (Re = 2.9E6) and 20 for the middle flow (Re = 1.6E6) since the middle flow was not included in the second day of testing.

<u>CFD Results for Ideal Conditions</u>:
The CFD modeling of pipe flow development starting from a uniform flow into the pipe inlet was done using the cross-sectional and longitudinal grid patterns shown in Figure 5; the mean velocity components: U, V, and W are those in the X, Y, and Z directions, respectively. The commercially available computer code known as CFX[1] was used; the NIST computational facilities used were workstation level computers. The computed pipe flows for Re = 3E6 attained distributions that came within specified percentages of the Bogue and Metzner profile as given in Table 1; see [5 and 7].

Table 1 presents the diametral pipe lengths required for the selected inlet flow distributions to develop to within 1% of asymptotic limits at the specified X, Y locations; the 1% value was arbitrarily selected as a reasonable value. The three criteria used in the table are:

(1) the mean axial velocity, W,
(2) the magnitude, q, of the sum of the root-mean-squares (r.m.s.) of the turbulent velocity components, and
(3) the azimuthal or swirl velocity component, V, along the X axis.

The maximum length requirement is given at the bottom of each column of data. The conclusion drawn from these results is that high Reynolds number (4.3E5) pipe flow requires very long lengths to attain distributions close to fully developed conditions. At higher Reynolds numbers, these lengths increase. Also, the axial velocity and the turbulent velocity values at the pipe centerline equilibrate within about 50 diameters for all conditions – including skewed or swirled inlet flow conditions. However, significantly

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greater lengths (68 diameters to >90 diameters) are required to satisfy our 1% criteria for off-centerline locations such as ± D/4 or ± 3D/8, where D denotes pipe diameter.

These development lengths are the longest for inlet flows having swirl; skewed distributions require longer lengths than uniform flow inlet profiles. These results were intended to guide the analyses of the Phase 1 testing program and to predict performance trends with Reynolds number. The computer simulations of ultrasonic techniques used non-reflecting, straight-line transmissions through the pipe centerline. The results are given below.

Computer Simulations of Ultrasonic Meter Performance in Ideal Pipeflows:
Detailed descriptions of the methods used to simulate ultrasonic metering techniques in incompressible and compressible flows are given elsewhere; see [7]. These results indicate that for low Mach No. i.e., M<0.1, the assumption of straight line ultrasonic wave propagation is quite adequate. Our simulation results shown in Figure 6 indicate that if travel-time ultrasonic flow meters use typically arranged paths through the center of the pipe and assume the pipe flow distribution is uniform, positive errors will occur; see [5,8-10]. These errors will range from 5% to 6.5% of the true value in our flow test range, depending upon which ideal flow distribution is selected. These errors depend also on Reynolds number, pipe roughness, inlet flow conditions, distance from the inlet, etc. It is also shown in Figure 6 that with increasing Reynolds numbers such errors decrease monotonically, for most fully developed pipe flow distributions. We note that the Gilmont distribution is developed mainly for lower Reynolds numbers (< 1E5); see [8]. We also note that meters that are properly compensated for these effects need to have the compensation made relative to the assumption of uniform flow; they also need the proper negative trend with increasing Reynolds number.

Meter simulations were also done using the profile measurements shown in Figure 2, assuming that axial gradients in these profiles are negligible. Results are given in Figure 6. The data denoted LDV-H and LDV-V show the error levels that would occur if the meter were installed horizontally and vertically, respectively, and operated with the assumption that the pipe flow profile is uniform. In spite of our extensive efforts to condition our pipe flow to attain ideal installation conditions, our test flows only approximated the Bogue & Metzner distribution, as shown in Figure 2(a). In these flows, our horizontal simulation results fall 0.5% to 1.7% below the band of errors given by the Bogue & Metzner, Reichardt, Log, and Power Law distributions; see [5,8-10]. We estimate that the LDV results shown in Figure 2(a) are within 1% of the true values, and conclude that these simulation results are due to the LDV values lying, for the most part, below counterparts in the respective Bogue & Metzner distributions in Figure 2(a). For both horizontal and vertical profiles, these simulation results show a decreasing error trend with Reynolds number; for the horizontal profile this slope closely matches that for all the distributions, excluding the Gilmont, which, as mentioned above, is for lower Reynolds numbers.

Results and Discussions of Meter Tests:
Figure 7 presents real-time data recorded during a typical test sequence. It consists of five gravimetric determinations of flow rate using NIST's reference standards and the periods between these when the water was being drained back into the reservoir and instruments were being re-set for the successive collection. The data plotted in Figure 7 was recorded at the highest rate that each meter could produce its results. The left ordinate is the deviation of each signal from its average value during this 20 min interval. Figure 7 plots results from a typical participant, denoted by "A"; it also contains time traces from the in-line ultrasonic and magnetic flow meters, denoted "Ref U" and "Ref M", respectively. The flag signal is also plotted in Figure 7; this binary signal indicates by "1" when the water was being collected in the gravimetric system. The right ordinate indicates this binary flag signal.

The scatter in Figure 7 is produced by several factors. These include the strategies selected for measuring ultrasonic travel times, the meter's response in this installation, its performance characteristics in measuring this flow, and the turbulence in this pipe flow. The short term excursions of the reference meter indications were as large as 2%. Although difficult to read in this Figure 7, the more slowly read responses of the participating unit vary about 0.5%; this will be seen more clearly in the following figures.

Figure 8 expands a typical data record for the same participating unit during a single collection period so that the meter responses during one 2 min period can be seen more clearly. Note that, according to all three meters, the flow rate does not decrease during the collection interval despite reservoir depletion as water is being collected in the gravimetric flow standard. Also note that these three flow meters have different response times. These response times are the results of the sensing times associated with the meter's hardware and the processing times in the meter's software.

Figure 9 shows the data record from Figure 7 with the following refill period. Again, no monotonic variations in the flow are evident either during water collections or in the refilling periods.

Figure 10 shows a typical record where the data is averaged using a 20 s, moving average technique. The fluctuations compared to those shown in Figure 7 are considerably reduced for the reference meters, but those for the participating unit are relatively unchanged. This happens because this participating unit was averaging more slowly than the reference meters.

Figure 11 plots error assessment data for all participating units for the lowest and highest test flows. Most of these units were installed essentially horizontal, i.e., within small angular orientations about the horizontal plane on the test pipe. Six data sets are presented because one of the participants had to re-test. The points plotted are the participant's averages during the collection runs. The ordinate scale is the error i.e., the difference between each of these participant's averages and the NIST standard, expressed as a percentage of the NIST result. Error bars show one standard deviation of the deviation about the mean value. These error bars provide an indication of the "single reading" imprecision of the meter under test. Excluding meters for which extremes occurred: 1) in percentage error (D), and 2) in deviations from means (E), these results show errors that are predominately positive, ranging from about +1 to +3%, with most values in the range from +2% to +3%. For these participants, standard deviations of temporal variations ranged up to 0.5%. These participants seem to be compensating somewhat for profile effects. This is apparent from the fact that Figure 6 shows that errors of +5% and +4% would result if the flow profile was assumed uniform at the low and high flow conditions, respectively. However, as the LDV-H simulation results fall 0.5% to 1.7% below the band of simulations for the Bogue & Metzner, Reichardt, etc. profiles, one would expect that, if these participants compensated for these ideal flow distributions, the results in Figure 11 would be -0.5% to -1.7%, instead of +2 to +3%. It is also noted that in Figure 11 the error usually increases with increasing Reynolds number as opposed to the negative trends expected from Figure 6. Therefore, we conclude that both flow profile compensation and its trend with Reynolds number need to be reconsidered by these manufacturers.

Figure 12 plots error assessment results for the medium flow. These results fall within those for the lowest and highest flows.

Figure 13 compares errors for the participating meters to those for two reference meters at the high flow. It is noted that the reference meters have errors nearly always less than 0.5%. In what follows, these performance levels will be more clearly quantified.

Figure 14(a) presents mean values and repeatability results for all participants; Figures 14(b) and (c) clarify these by showing results for the low and high flows, respectively. The data plotted are the means of the five successive error assessments of participants' results obtained in each of the six tests, denoted T1, ..., T6. Mean values mostly range from –1% to +3%; the worst case error is –14%, but this occurred for only one participant (D). Error bars quantify repeatability, which is here defined as one standard deviation of the five successively determined error assessments about their mean values. It is in the range of ±0.1% to ±0.2% for most of these manufacturers; the worst case is ±2%, but this occurred for only one participant (E). As noted above, the mean values in Figure 14 are lower than values expected from the LDV-H results in Figure 6 if uniform flow was assumed. As also noted above and excluding the results shown for participant D, if these participants were compensating for profiles such as Bogue & Metzner, Reichardt, etc., low flow results would be in the range from -0.5% to -1.5% as opposed to 0.5% to 3.5%. Similarly, high flow results would be in the range from -0.8% to -1.7% as opposed to -1% to +3%, if compensations were based on Bogue & Metzner, Reichardt, etc. Figure 14(a) also shows error trends with Reynolds number for these mean value results that are more consistently positive than the negative one expected via Figure 6. Therefore, the earlier conclusions regarding profile compensation and its trend with Reynolds number made for the individual error assessments apply to these mean value results as well.

Figure 15 presents mean values and reproducibility results for all participating meters for all flow rates. Reproducibilities are here defined as the standard deviation of the mean for: (1) the ten values at each flow in tests T1 and T2 and in tests T3 and T4, (2) the twenty values in tests T1 through T4 at each flow, and (3) in tests T1 through T6 at all flows except the middle one, which was excluded from tests T5 and T6. Figure 15 shows mean values of these error assessments are mostly in the range from 0.5% to +3%; the worst case is –13.5%, but this occurred only for participant (D). Reproducibilities are in the range from ±0.1 to ±3%, but three participants have reproducibilities of ±1%, or better. From these impressive results, we conclude that, if NIST calibrations were to compensate for these mean value errors, these units could attain performance levels commensurate with these reproducibility levels, of ±1%, or better.

Figures 16-18 present error assessment results for the in-line ultrasonic flow meter as obtained during the six tests of the participating meters. Figure 16 shows mean values of this meter's output for each run of all three flows as assessed using NIST's flow standards. Error bars show one standard deviation of the time-varying meter indication about its temporal mean. Figure 17 shows repeatability results for the six tests with error bars showing one standard deviation of the five successive measurements about their mean. Prior to the participant B tests a minor software change was made to enhance noise suppression capabilities. Figure 18 gives reproducibilities, as defined above, with error bars showing one standard deviation of the respective values about their mean. These results show error levels, for the medium and high flows, of 0.2% or better with repeatabilities, and reproducibilities of 0.2 % or better. This meter was not calibrated by its manufacturer; its results are based on length and time measurements. We conclude, therefore, from this impressive performance at these higher flows, that it may be feasible to develop this technology into the status of a primary flow standard. If this development were to occur, it would extend the capabilities of flow laboratories for establishing and maintaining traceability to national standards.

Figure 19-21 present results for the in-line magnetic flow meter as obtained during the six tests of the participating meters. Figure 19 shows mean values of this meter's output for each run for all three flows as assessed using NIST's flow standards. Error bars show one standard deviation of the time-varying meter indication about its temporal mean. Figure 20 shows repeatability results for the six tests with error bars showing one standard deviation of the five successive measurements about their mean. Figure 21 gives reproducibilities, as defined above with error bars showing one standard deviation of the respective values about their mean. It is concluded that for the medium and high flows, this meter's results show mean values of error levels, for five assessments using NIST's flow standards, of 1% or better and repeatabilities and reproducibilities of 0.5% or better.

Conclusions:

The specific results of these Phase 1 tests of these clamp-on units, are:

1) Errors as obtained by averaging meter outputs range, for the most part, between +2% to +3%; worst case error is –14%, but this occurred for only one manufacturer.
2) Repeatabilities, as defined by the standard deviation of five successively determined error assessments about their mean value, are in the range from ±0.1% to ±0.2% for most participants; worst case repeatability is ±2%.
3) Reproducibilities, as defined by the standard deviations of error assessments made under a variety of conditions considered typical of normal meter usage, range up to 3%. However, 3 of the 6 sets of results show reproducibilities bounded by 1%.
4) The low flow results are the most varied; the high flow results are least varied.
5) The different "zero flow" conditions designed into these tests did not cause different performances.
6) The remove-replace conditions designed into these tests did not cause different performances.
7) Computer simulations of the travel-time ultrasonic techniques used by these clamp-on meters show that errors in the conditions used for these tests should range from +4% to +5% if the meter operation used the assumption that the pipe flow profile being measured is uniform. If meter operation compensated for Bogue & Metzner or Reichardt type profiles, simulations in these test conditions show that the results should be in the range –0.5% to –1.7%. Since the error assessments found lie mostly in the range from +2% to +3%, we conclude that these manufacturers do seem to be compensating for profile effects, but the compensations could be improved.

8) Errors generally increase with Reynolds number, while computer simulations show these trends should decrease whether the pipe flow is assumed to be that of Bogue & Metzner, Reichardt, etc. Therefore, the compensations used in these meters need improvement.

For the ultrasonic reference meter used in these tests, the average errors for the two higher flows are 0.2% or better, and repeatabilities are 0.2% or better. This meter was not calibrated by the manufacturer; it was set up to operate in ideal flow conditions using only length and time standards. Its impressive performance at these higher flows indicates that it may be feasible to develop this technology into the status of primary flow standards. If this development were to occur, it would extend the capabilities of flow laboratories for establishing and maintaining flow measurement traceability to national standards.

The magnetic reference meter used show averaged errors ranging to 1% or better, and repeatabilities are 0.5% or better.

We conclude that clamp-on type, travel-time ultrasonic technology has progressed very well. Concerns regarding "zero flow" set requirements and "remove-replace" variations, dating to the early stages of ultrasonic meter development, no longer seem valid. Although the "remove-replace" variability obtained in the present tests was achieved with the meter manufacturers doing the "remove-replace" changes, we conclude that if meter buyers are properly trained, they should be able to attain similar levels of performance.

The present Phase 1 tests in ideal installation conditions will serve as a proper reference for the planned tests in non-ideal flows downstream of a single elbow in Phase 2 and downstream of a concentric reducer in Phase 3. The results of these all these tests ought to have significant benefits to actual metering practice.

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Table 1. Pipe Lengths, in Diameters, Required to Develop Pipe Flow Profiles to within 1% of Their Asymptotic Limits

Position		Criteria Used	Inlet Velocity Profiles for Re=427,000				
X	Y		Uniform	Fast core	Slow core	Skewed(Y)	Swirled
0	0	W	42	38	51	50	49
		q	35	28	42	40	40
D/4	0	W	24	27	20	38	16
		q	28	23	35	30	32
		swirl V	-	-	-	-	>90
0	D/4	W	24	27	20	68	16
0	-D/4	W	24	27	20	65	16
3D/8	0	W	16	14	23	8	19
		q	19	20	26	22	29
		swirl V	-	-	-	-	90
0	3D/8	W	16	14	23	69	19
0	-3D/8	W	16	14	23	64	19
Maximum requirement			42	38	51	69	>90

1. By fast core is meant two, axisymmetric uniform flows: the center core is a radius in diameter and has a velocity about 15% faster than the uniform flow; the annular flow satisfies continuity.
2. By slow core is meant a flow analogous to the fast core but 15% slower than uniform.
3. By skewed in Y is meant the velocity varies linearly in Y from a 15% deficit at one pipe wall to a 15% excess at the other.
4. By swirled is meant an axisymmetric uniform flow with a solid body rotation over the central, radius-in-diameter core of fluid that maximizes to 15% of the uniform velocity; this is surrounded by an irrotational vortex flow that spins down to 5% of the uniform value at the wall.

Test Configuration For Ideal Installation Conditions

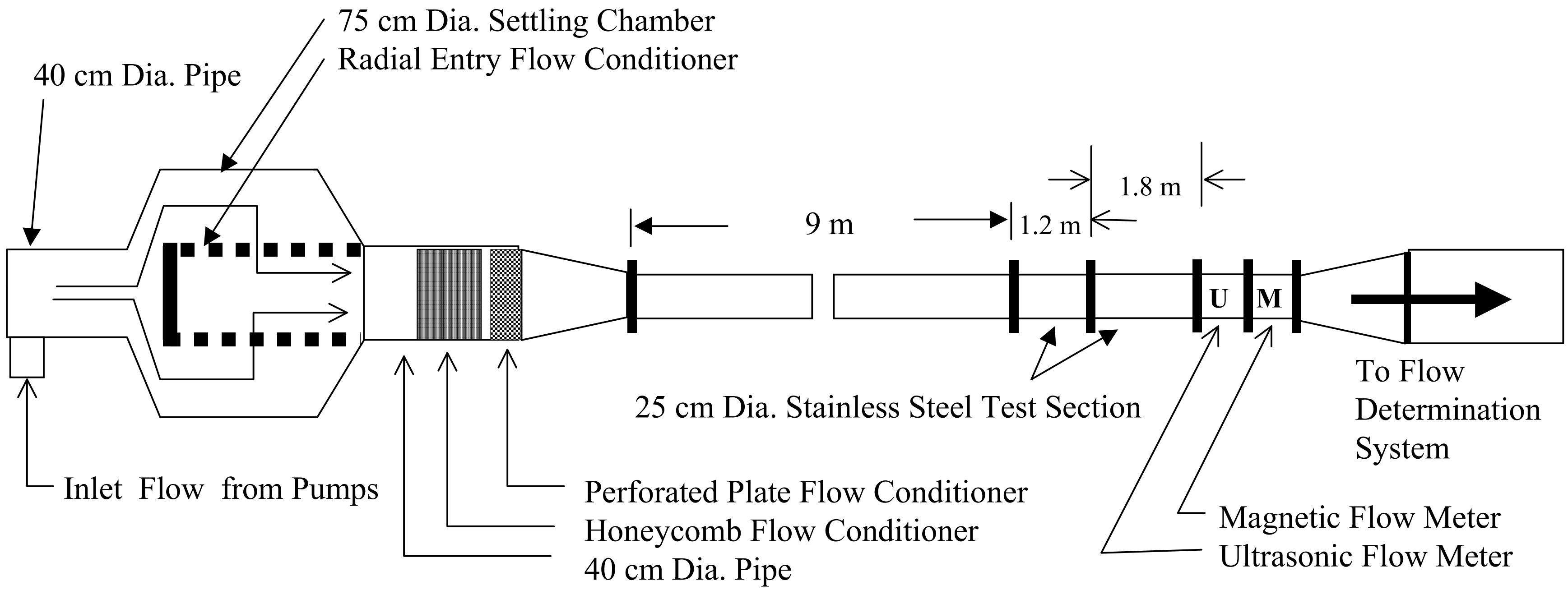


Figure 1. Sketch of the Piping Arrangement Used for Phase 1 Testing. The right-handed coordinate system has the origin on the pipe centerline at the entrance to the 25 cm pipe section; the Z direction is axial with the flow, the Y direction is vertically upward, and the X direction is horizontal. The velocity components in these directions are: W, V, and U, respectively.

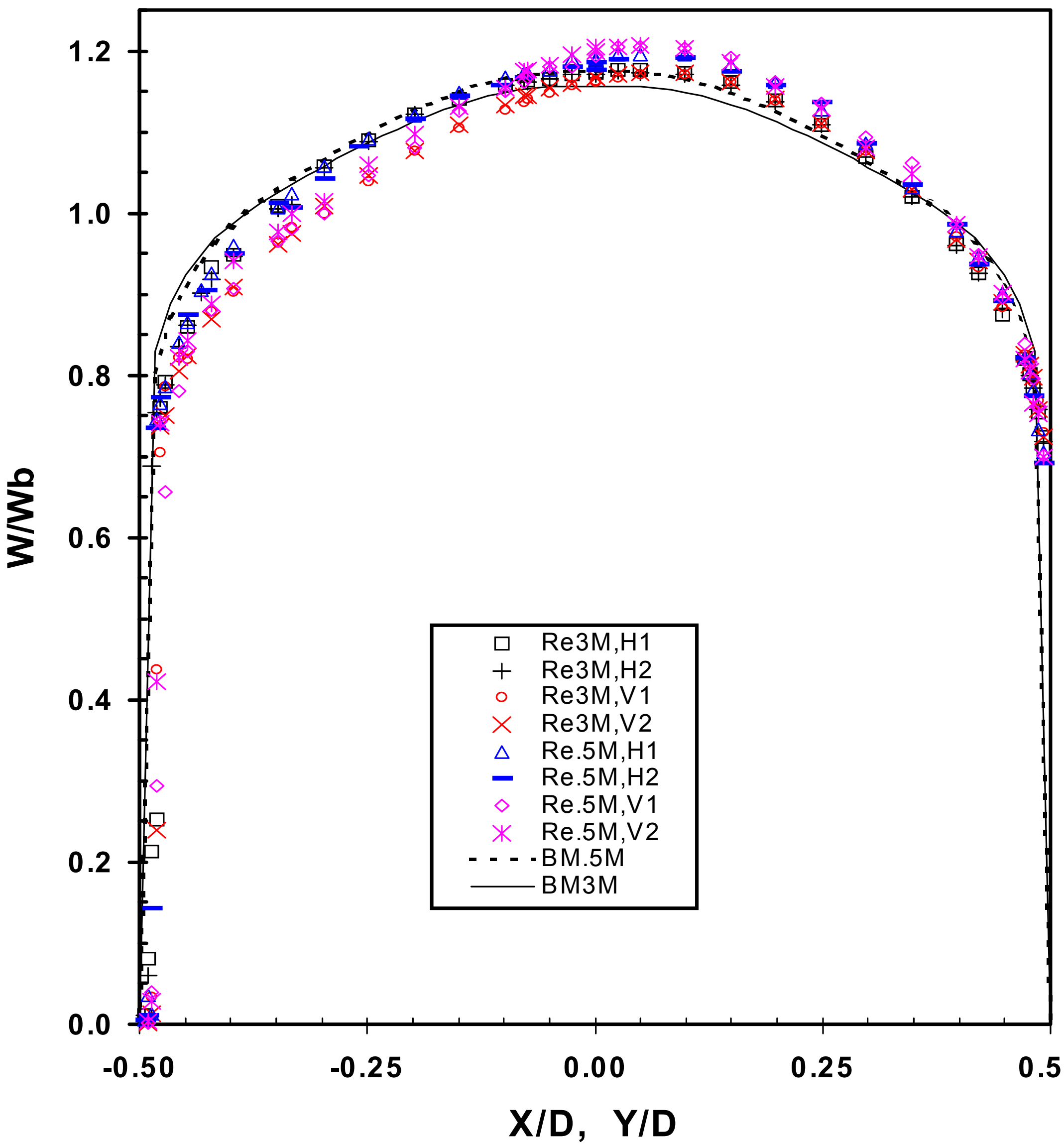


Figure 2(a). Pipe Flow Characteristics: Mean Axial Velocity Profiles. These LDV results were measured over horizontal and vertical diameters for the lowest and highest flows used for testing. Notations are: W is the mean axial velocity; W_b is the bulk average velocity determined using NIST's Gravimetric Standards; X/D and Y/D are, respectively, horizontal and vertical distances in diameters from the pipe centerline; Re is the Reynolds number; H1, H2 denote, respectively, initial and repeated horizontal profile measurements; and V1, V2 denote vertical counterparts. The lines show the Bogue & Metzner profiles for: Re=3E6, the solid line; Re=5E5, the dashed line.

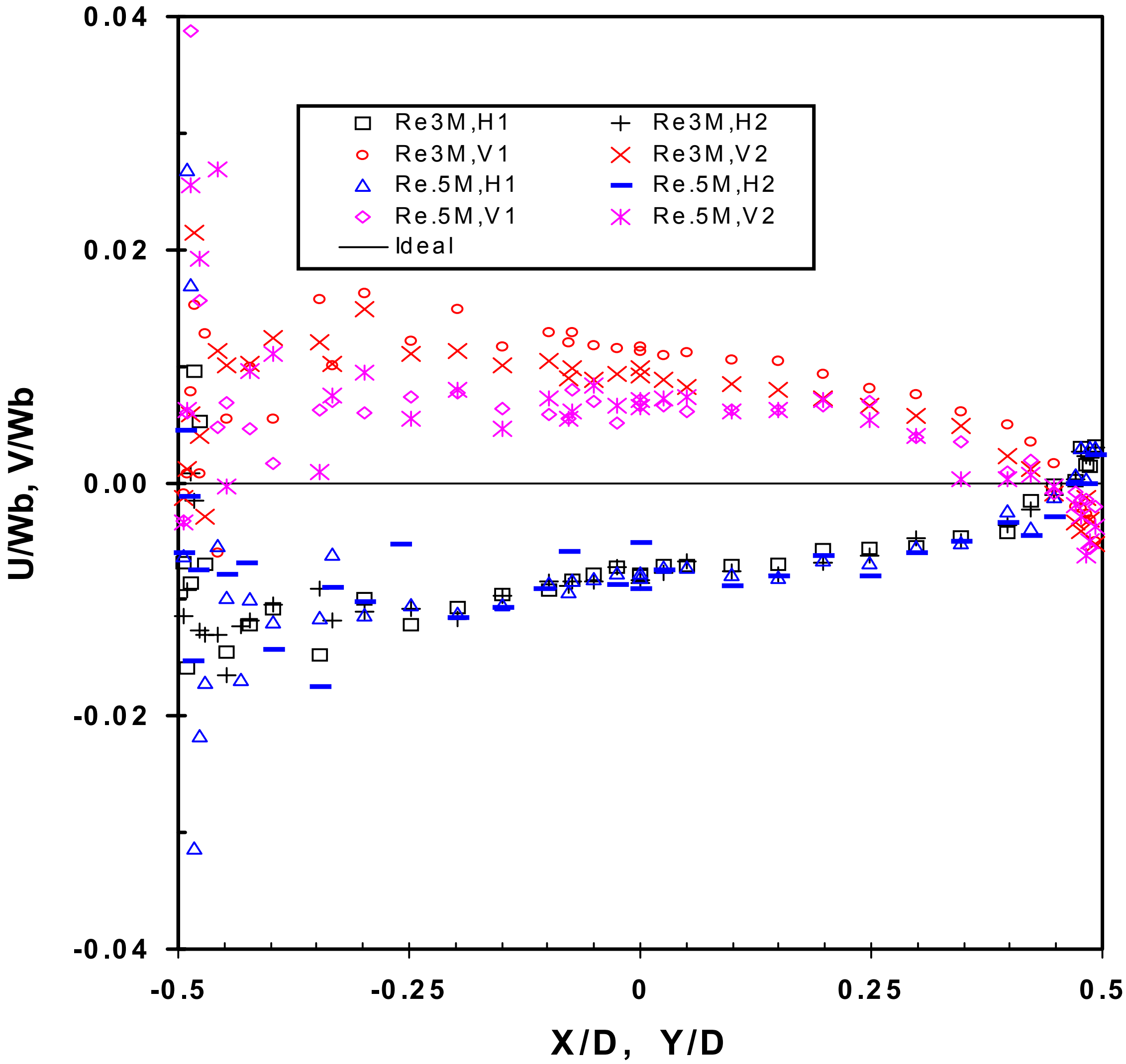


Figure 2(b). Pipe Flow Characteristics: Mean Transverse Velocity Profiles. These LDV results were measured over horizontal and vertical diameters for the lowest and highest flows used for testing. Notations are: U and V are the mean transverse velocities along the vertical and horizontal diameters, respectively; W_b is the bulk average velocity determined using NIST's Gravimetric Standards; X/D and Y/D are, respectively, horizontal and vertical distances in diameters from the pipe centerline; Re is the Reynolds number; H1, H2 denote, respectively, initial and repeated horizontal profile measurements; and V1, V2 denote vertical counterparts. The zero ordinate denotes the ideal transverse velocity profile.

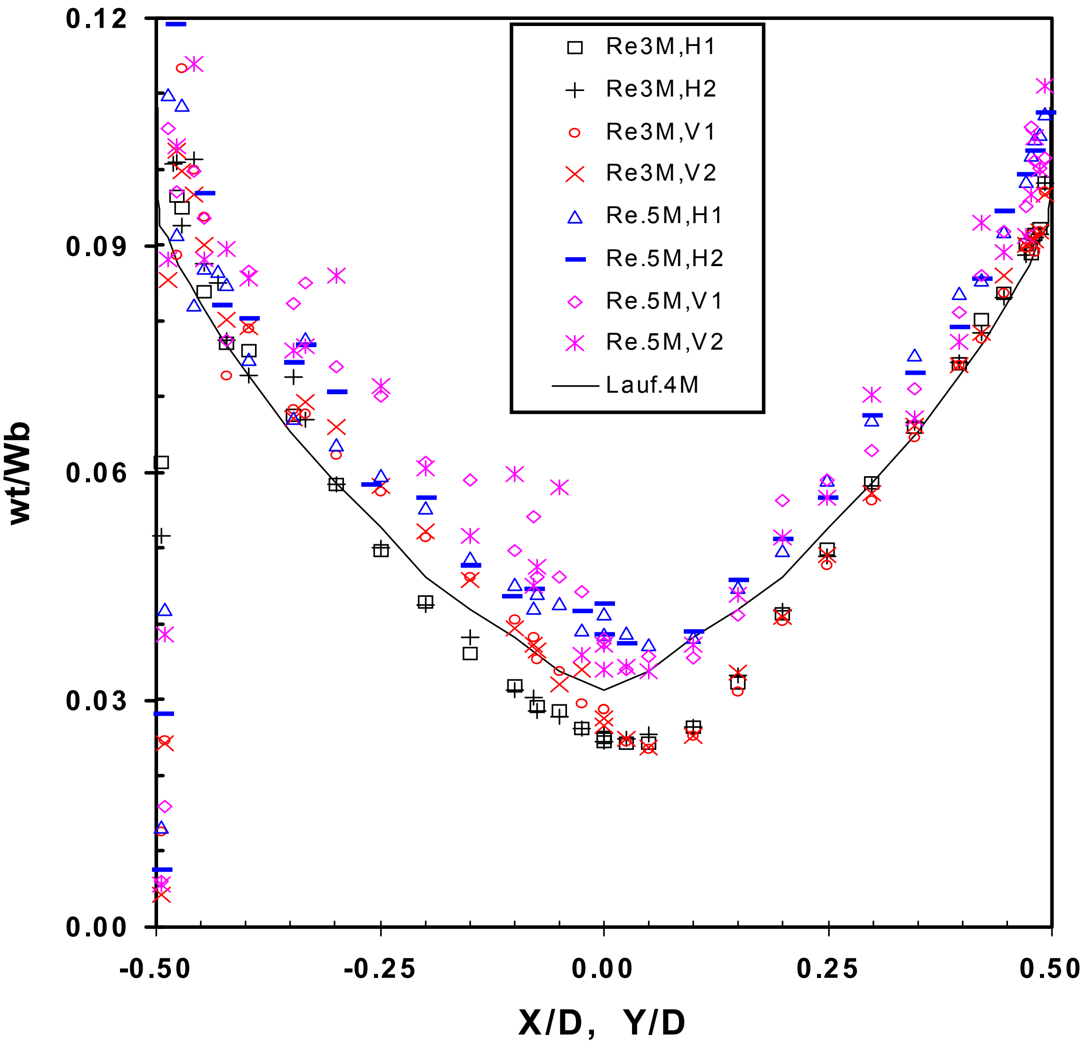


Figure 2(c). Pipe Flow Characteristics: Axial Turbulence Intensity Profiles. These LDV results were measured over horizontal and vertical diameters for the lowest and highest flows used for testing. Notations are: wt is the rms of the axial turbulent velocity, W_b is the bulk average velocity determined using NIST's Gravimetric Standards; X/D and Y/D are, respectively, horizontal and vertical distances in diameters from the pipe centerline; Re is the Reynolds number; H1, H2 denote, respectively, initial and repeated horizontal profile measurements; and V1, V2 denote vertical counterparts. The line shows Laufer's measured distribution for the axial component of the turbulence for Re=4.3E5, see [6].

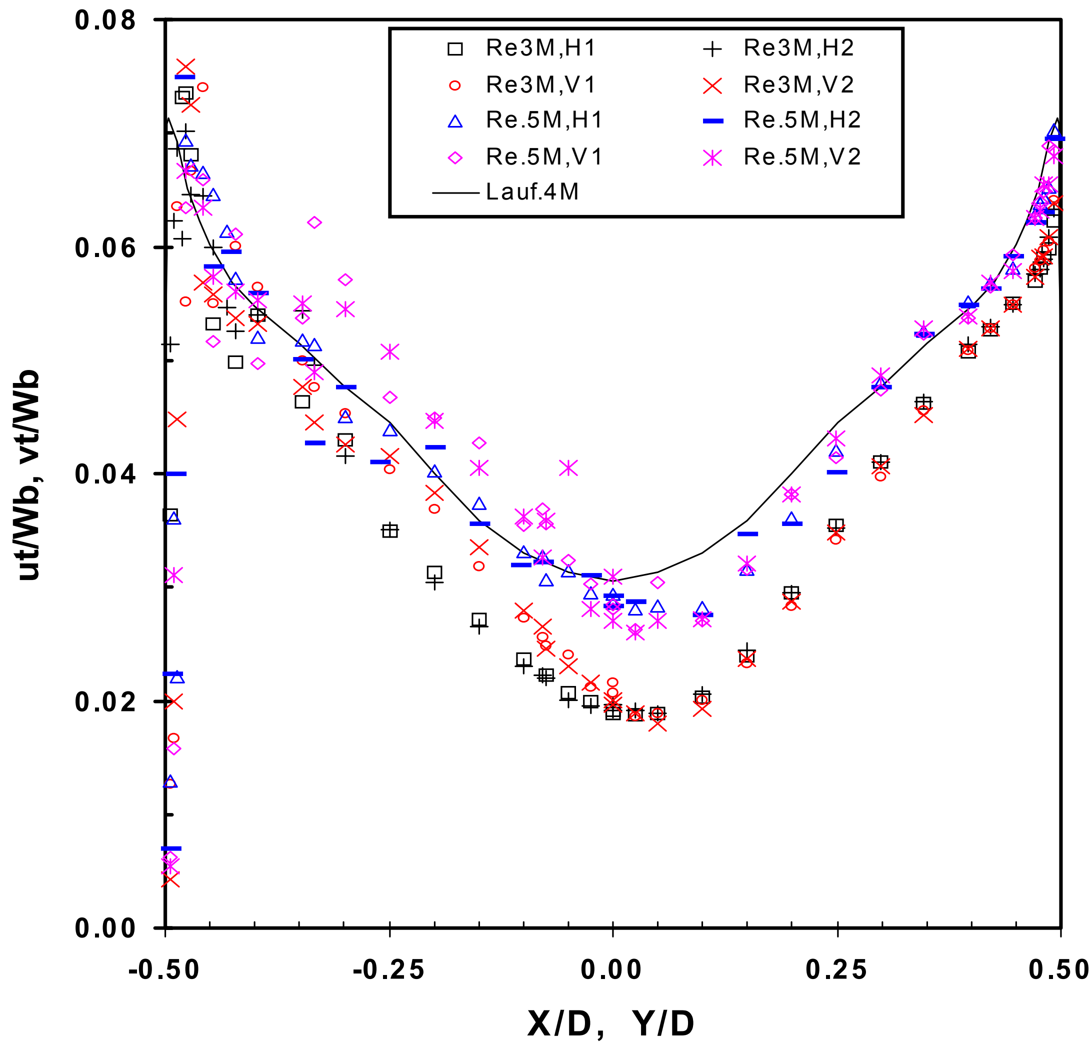
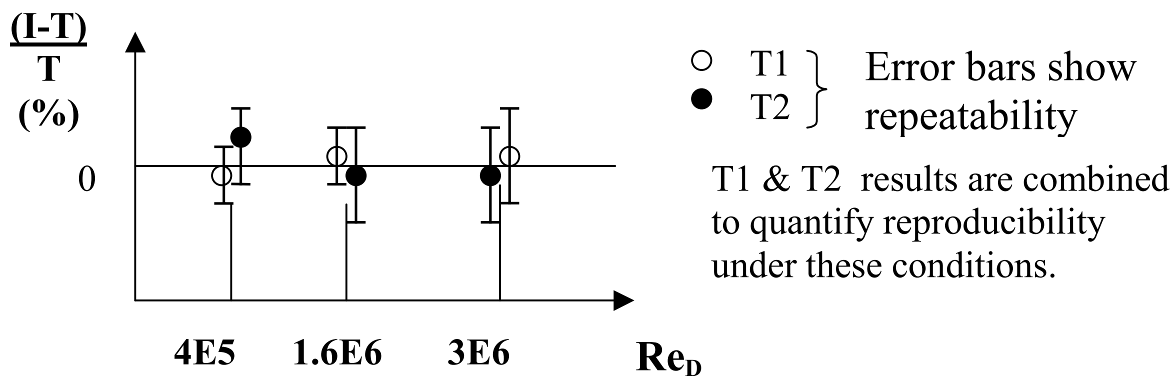


Figure 2(d). Pipe Flow Characteristics: Transverse Turbulent Intensity Profiles. These LDV results were measured over horizontal and vertical diameters for the lowest and highest flows used for testing. Notations are: ut and vt are the rms of the transverse turbulent velocities along the vertical and horizontal diameters, respectively; W_b is the bulk average velocity determined using NIST's Gravimetric Standards; X/D and Y/D are, respectively, horizontal and vertical distances in diameters from the pipe centerline; Re is the Reynolds number; H1, H2 denote, respectively, initial and repeated horizontal profile measurements; and V1, V2 denote vertical counterparts. The line shows Laufer's measured distribution for the transverse component of the turbulence for Re=4.3E5, see [6].

NIST Ultrasonic Technology Assessment Tests-Phase 1

Day 1:

I Repeatability and Reproducibility "w/o zero" set



II Repeatability and Reproducibility "w/zero" set

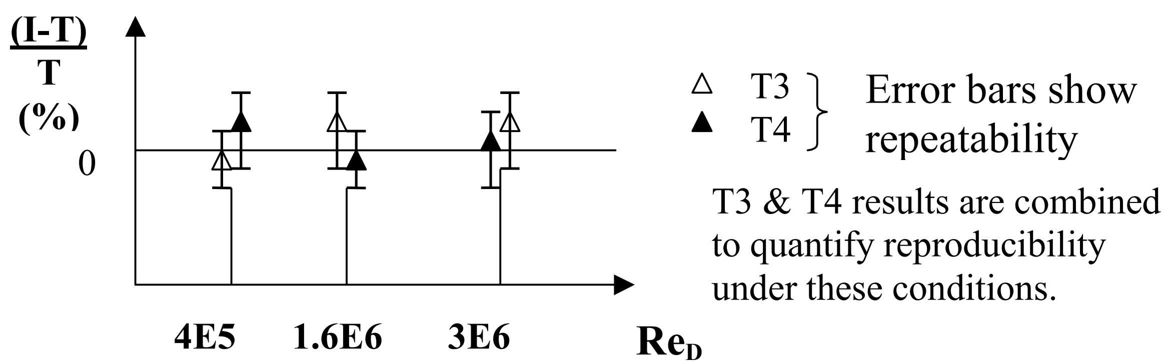


Figure 3. Sketch of the Tests and Data Presentation for the First Day. Symbols are averages of five successively determined differences between the averaged meter result, I, and the NIST gravimetric standards result, T, expressed as a percentage of the standard; error bars present one standard deviation of these five differences about their mean. Re_D is the diametral Reynolds Number. The symbols T1, ...,T4 identify the test conditions given in the text.

NIST Ultrasonic Technology Assessment Tests-Phase 1
Day 2:
III Remove-Replace Tests

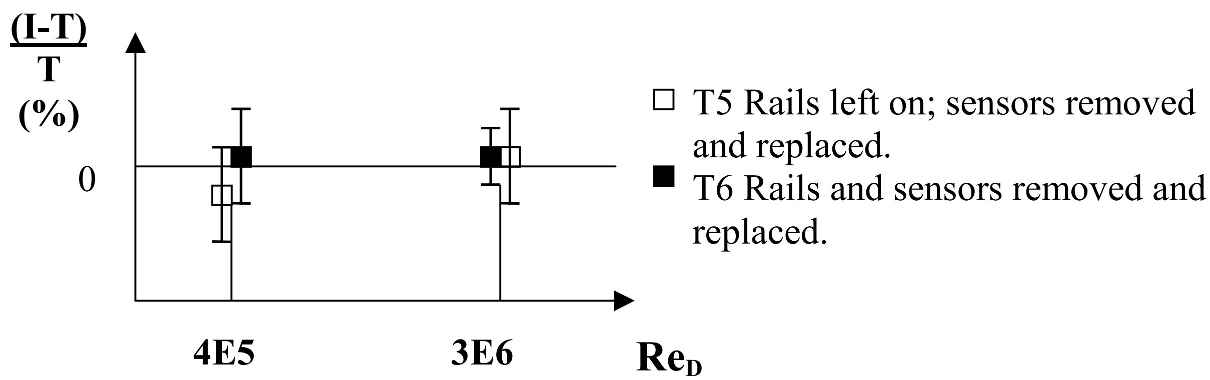
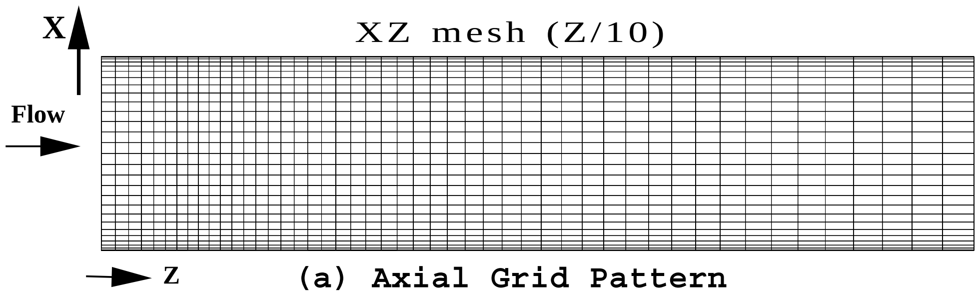
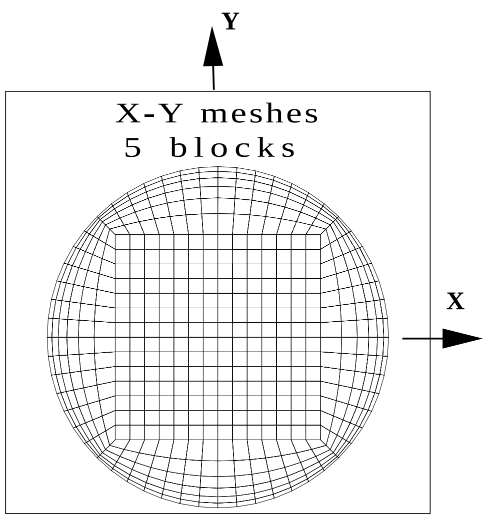


Figure 4. Sketch of the Tests and Data Presentation for the Second Day. Nomenclature is that described in the caption for Figure 3.

CFD Modelling of Long Straight Pipe Flows



(a) Axial Grid Pattern



(b) Cross-sectional Grid Pattern

Geometry Grid: **(CFDS−FLOW3D)**
Multi−Cuboid Block, Body Fitted Grid
5 Blocks in the circular cross−section with 532 elements
2 Sections in axial direction with 94 elements
Total cells= 94*532=50,008

General Flow Conditions:
3−D, Steady State
High Reynolds Number (427,000)
Turb.Model (RNG k−epsilon)

Inlet Flow Conditions:
Various Velocity Profiles
Constant turbulent velocity (9%) and dissipation.

Outlet Condition:
Mass Flow Boundary Conditions (Neumann B.C., zero Normal Gradient)

Wall B.C.: **Synthetic, Logarithmic Wall Profiles, No Slip**

Figure 5. Computational Grid Pattern and Conditions Used for Pipe Flow Modeling.

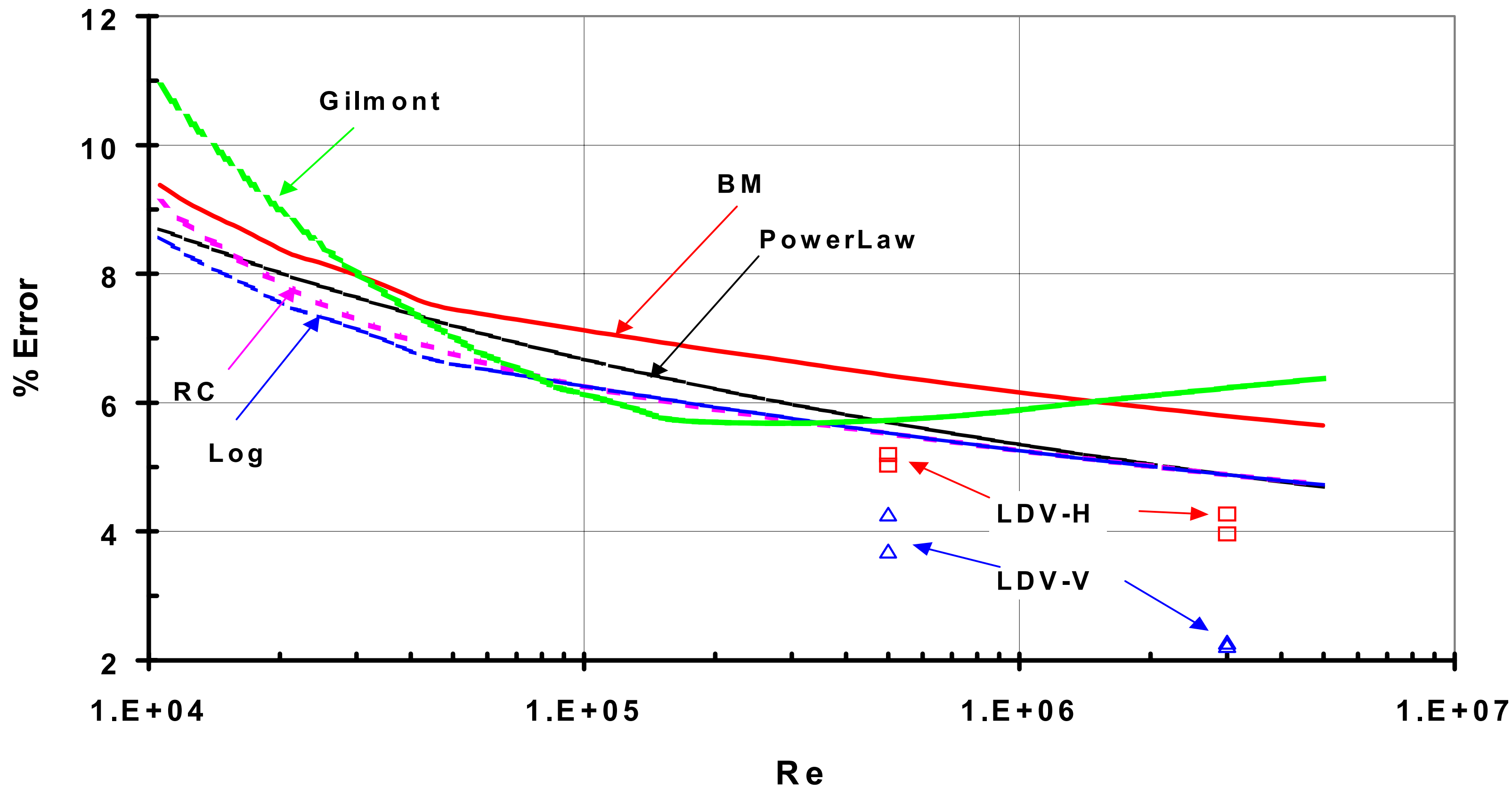


Figure 6. Meter Simulation Errors Resulting from the Assumption of Uniform Flow Profiles for Commonly Used Pipe Flow Distributions. Unnamed profiles are: BM refers to Bogue & Metzner, see [5]; LOG refers to logarithmic, see[10]; and RC refers to Reichardt, see [9]. The designations LDV-H and LDV-V refer, respectively, to the horizontal and vertical profiles plotted in Figure 2(a).

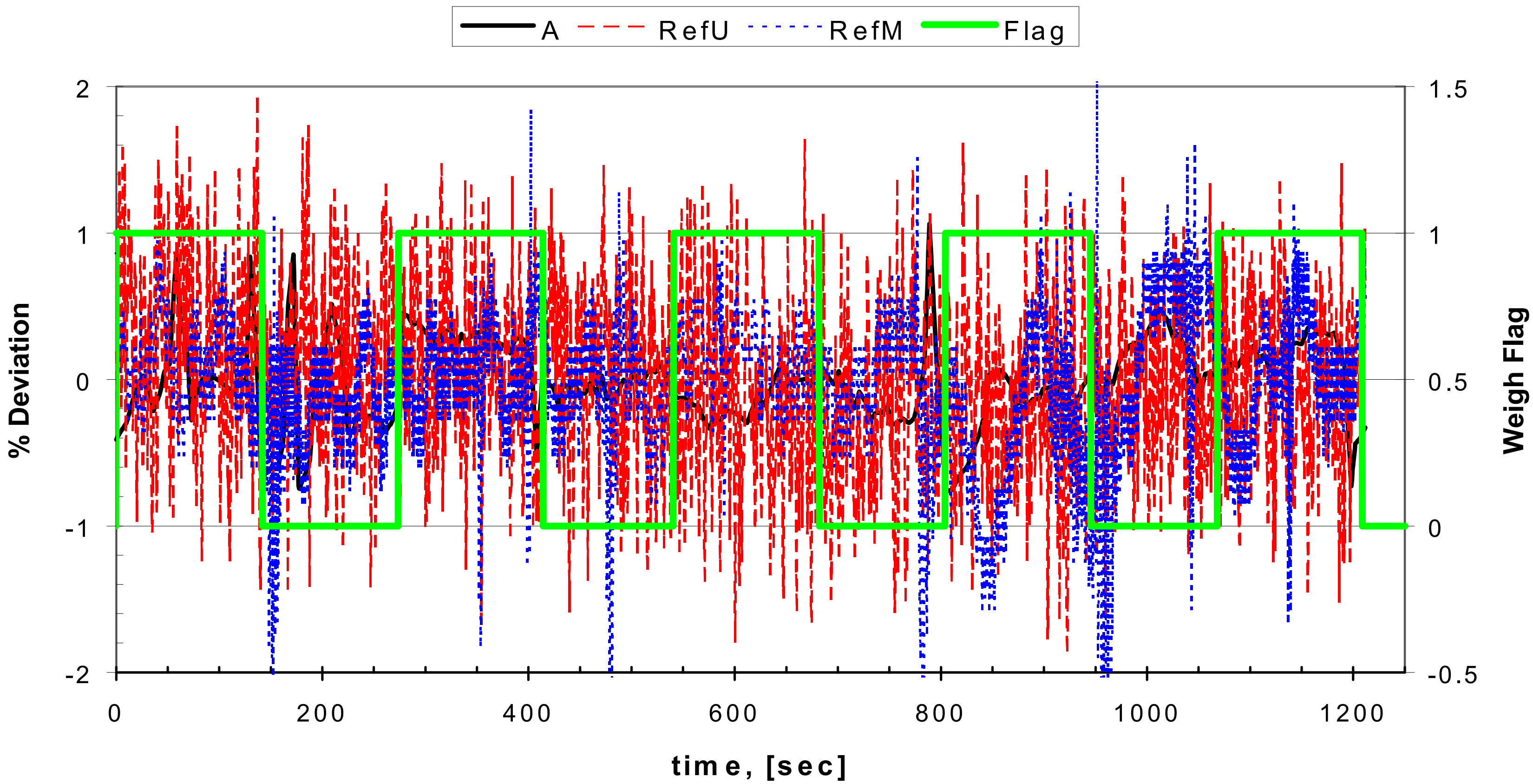


Figure 7. Typical, Real-time Data Record. The percentage deviation from the mean value is plotted for Participant A, the Ultrasonic Meter (RefU), and the Magnetic Meter (RefM) with the Weigh Flag (=1 indicating collection).

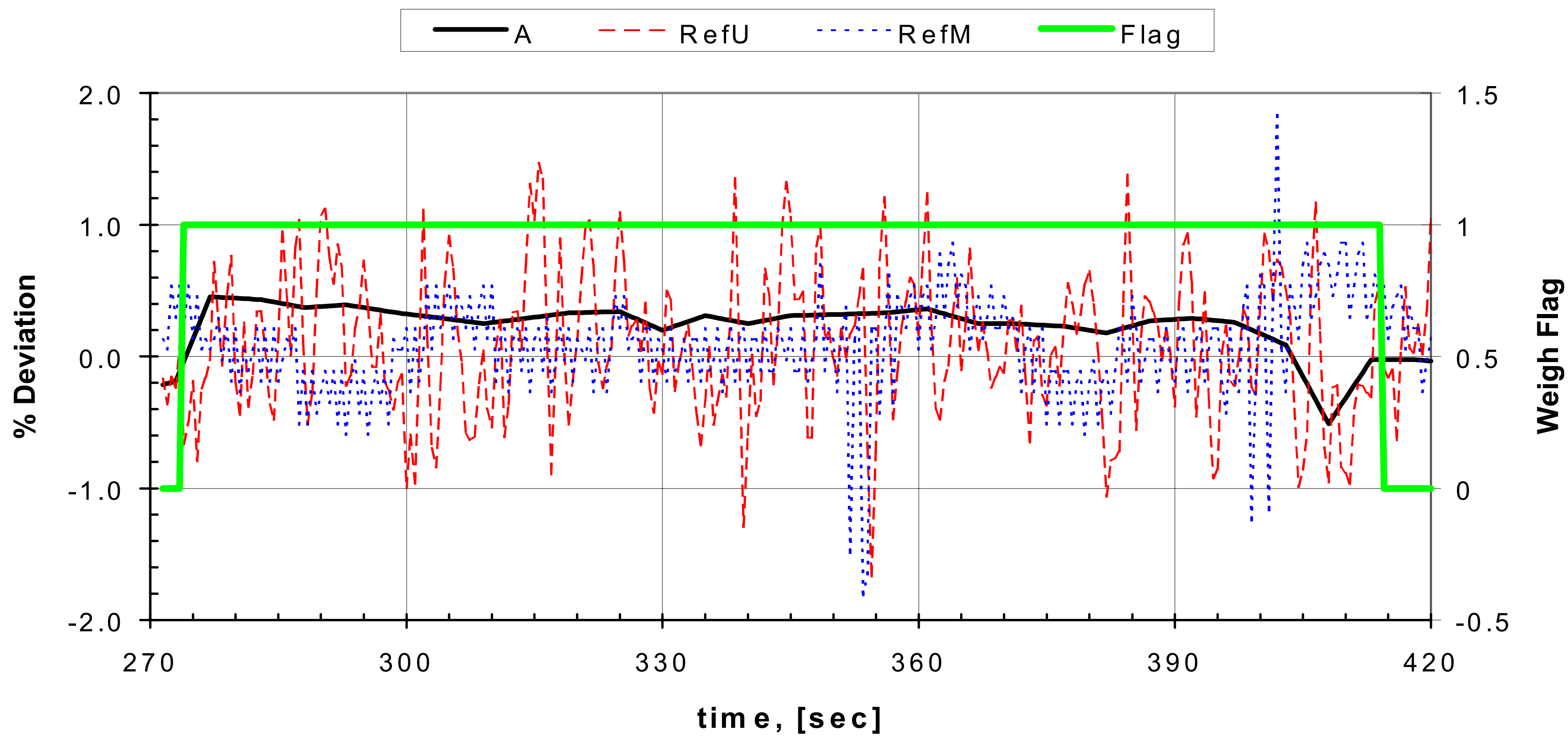


Figure 8. Typical, Real-Time Data Record. The percentage deviation from the mean values are plotted for Participant A, the Ultrasonic Meter (RefU), and the Magnetic Meter (RefM) with the Weigh Flag (=1 indicating collection).

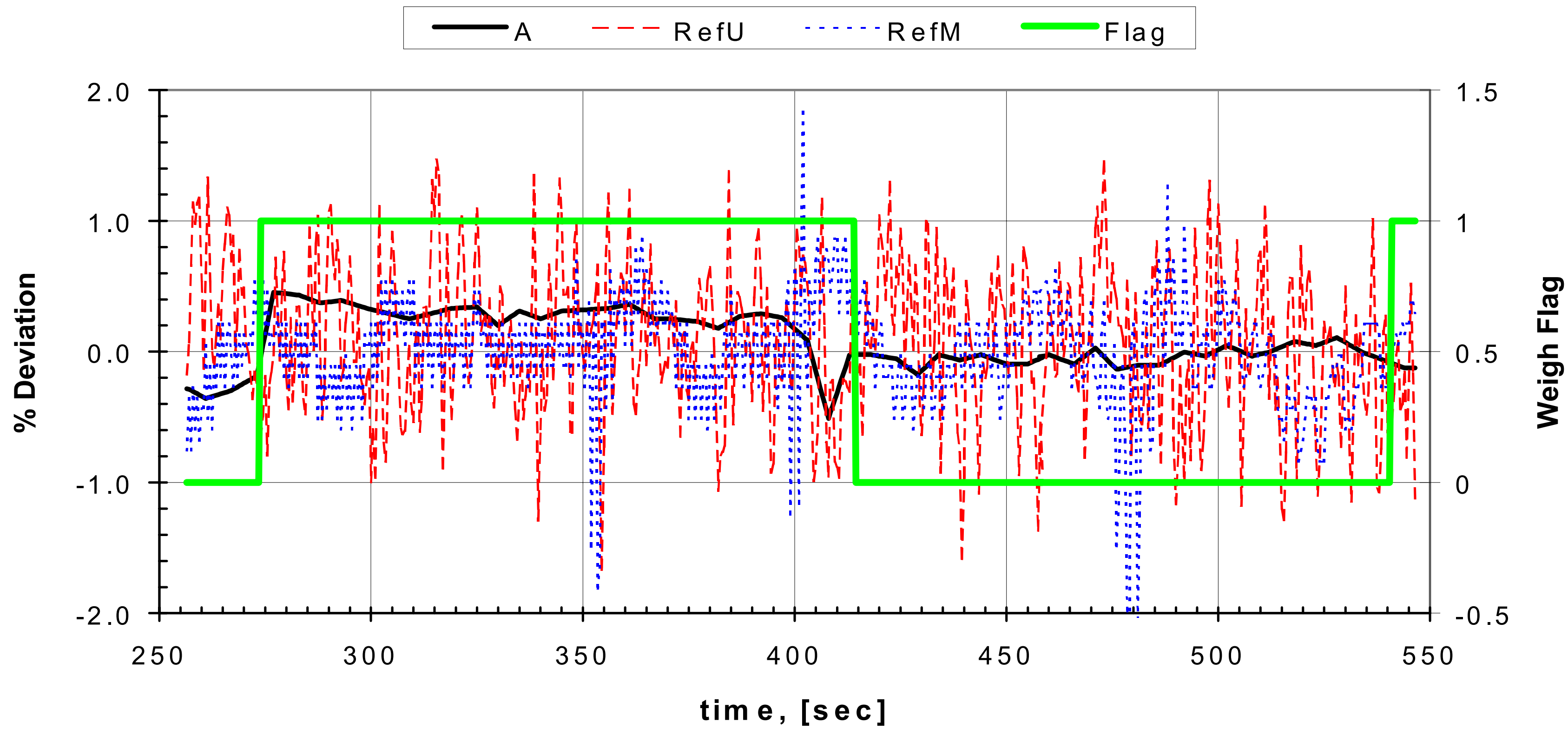


Figure 9. Typical, Real-Time Data Record. The percentage deviation from temporal mean value is plotted for Participant A, the Ultrasonic Meter (RefU), and the Magnetic Meter (RefM) with the Weigh Flag (=1 indicating collection).

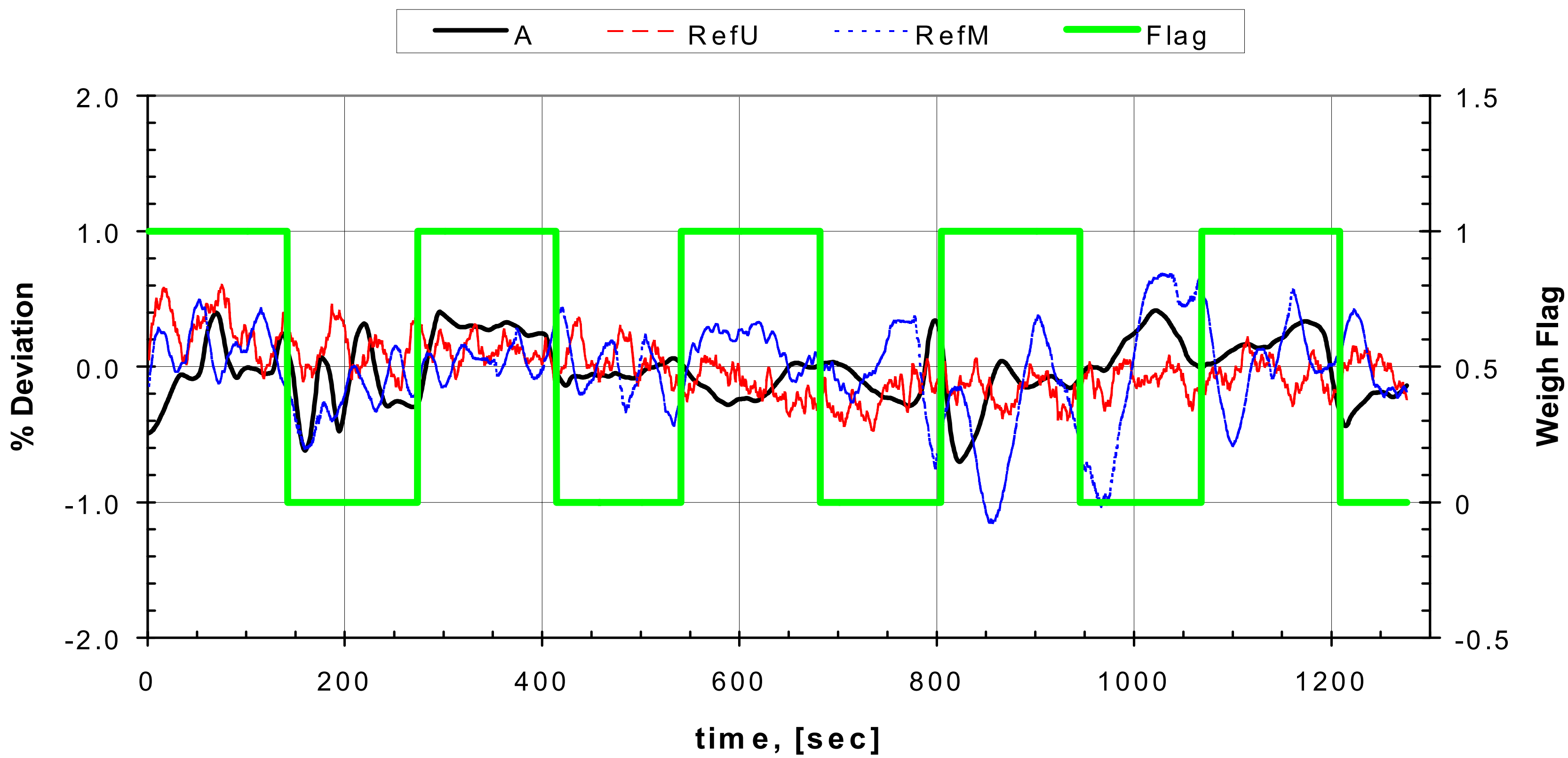


Figure 10. Typical Data Trace Using a 20 sec. Moving Average Technique on the Data Given in Figure 7. Nomenclature is same as that used previously.

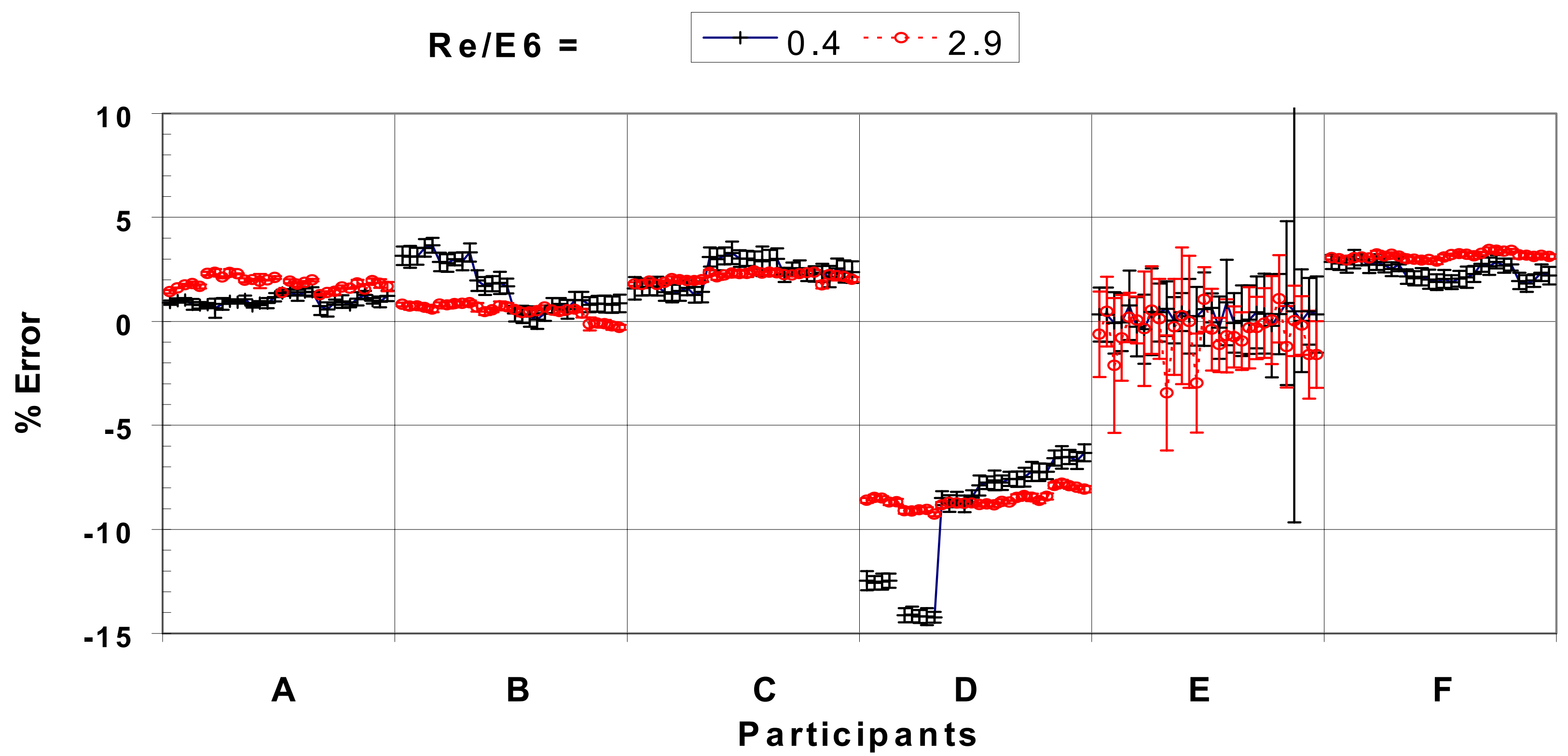


Figure 11. Error Assessment Data. The low and high flows were averaged over each flow determination and expressed as a percentage difference from the NIST gravimetric standards result. The data plotted sequentially, left to right, for each participant are the results from each timed collection performed in the six tests, T1-T6. Error bars show one standard deviation of the time varying meter indication about its temporal mean.

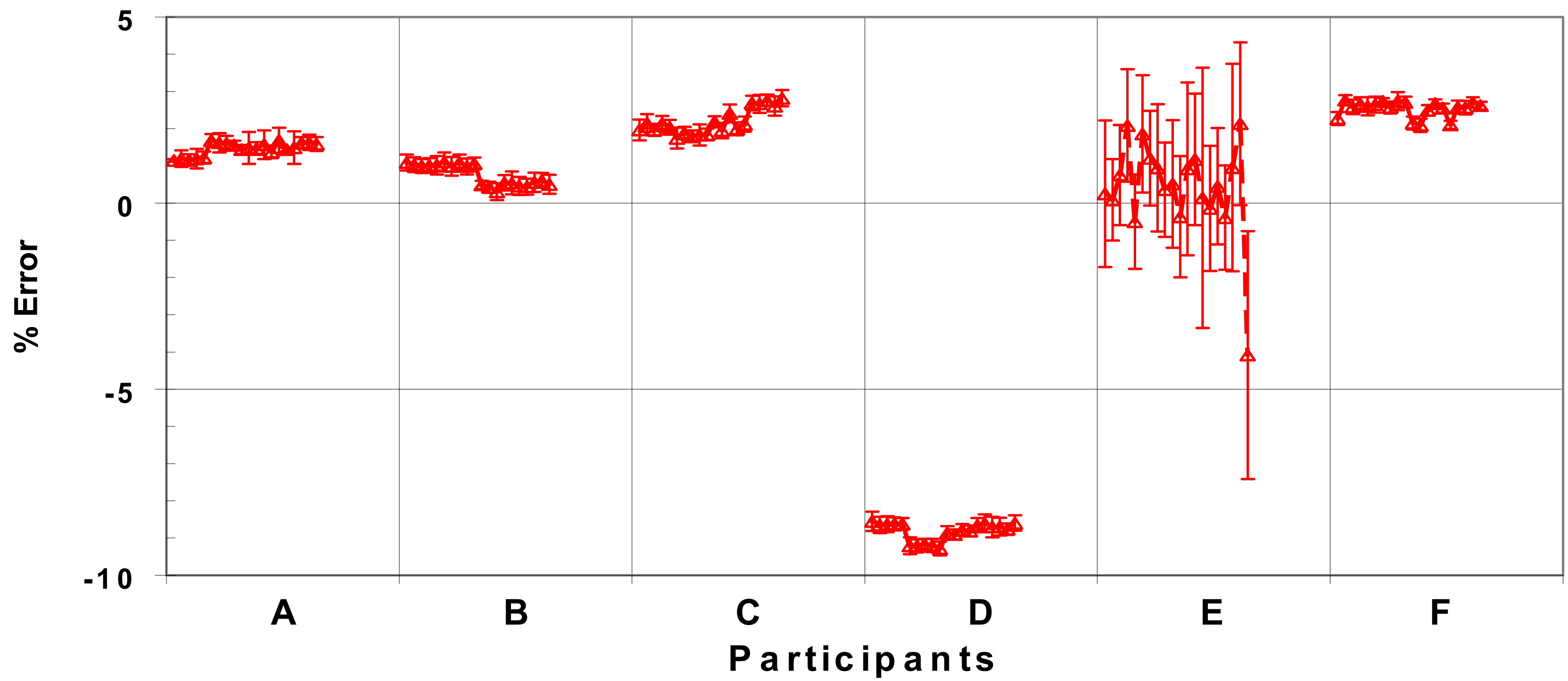


Figure 12. Error Assessment Data for the Re = 1.6E6. The flow rate is expressed as a percentage difference from the NIST gravimetric standards result. The data, plotted sequentially, left to right, for each participant, are the results for each timed collection in the four tests, T1-T4. Error bars show one standard deviation of the time varying meter indication about its mean.

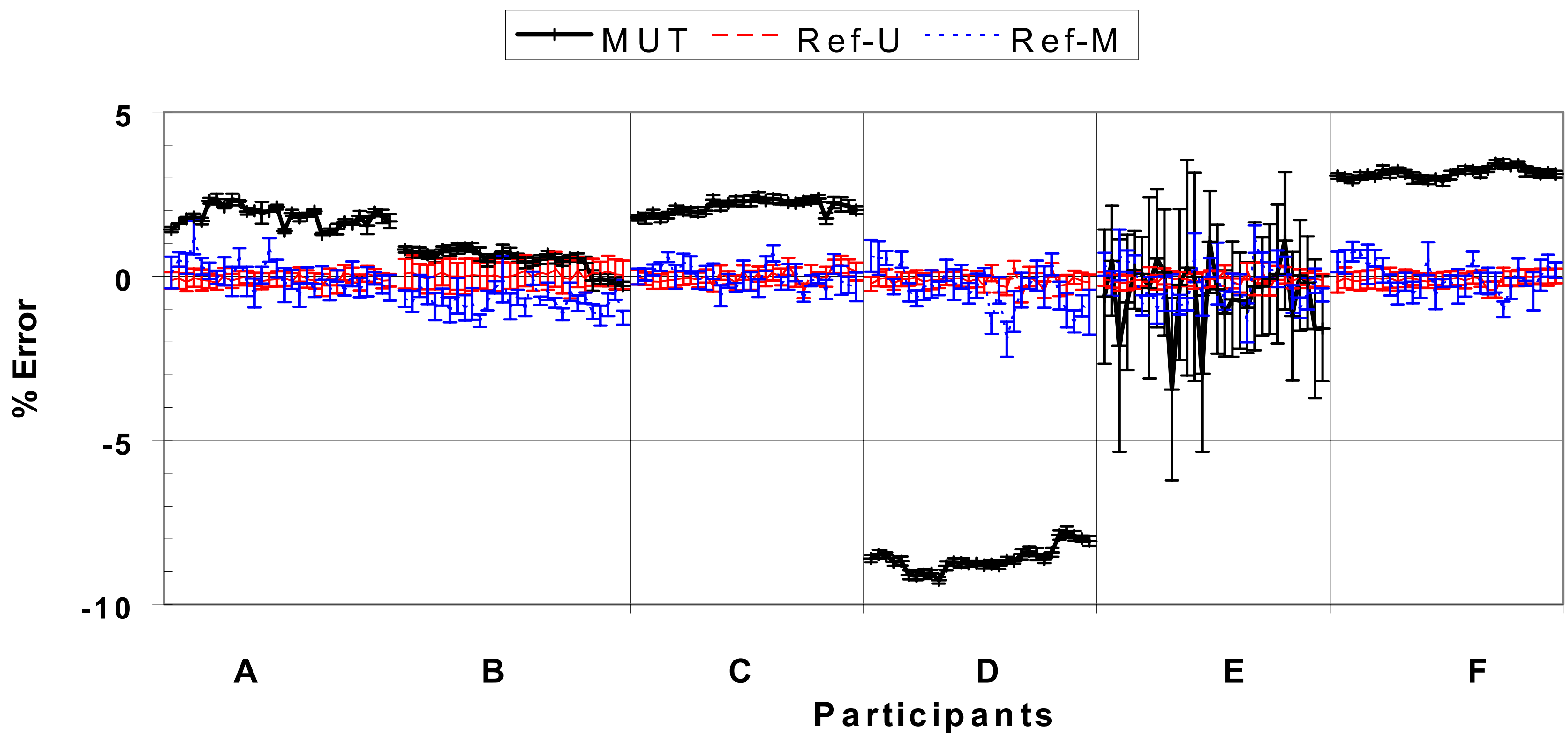


Figure 13. Error Assessment Data for Participating and Reference Meters for Re = 2.9E6. Results are expressed as a percentage difference from the NIST gravimetric standards result. The data, plotted sequentially, left to right, are the results for each timed collection for the six tests, T1-T6. Error bars show one standard deviation of the time varying meter indication about its mean.

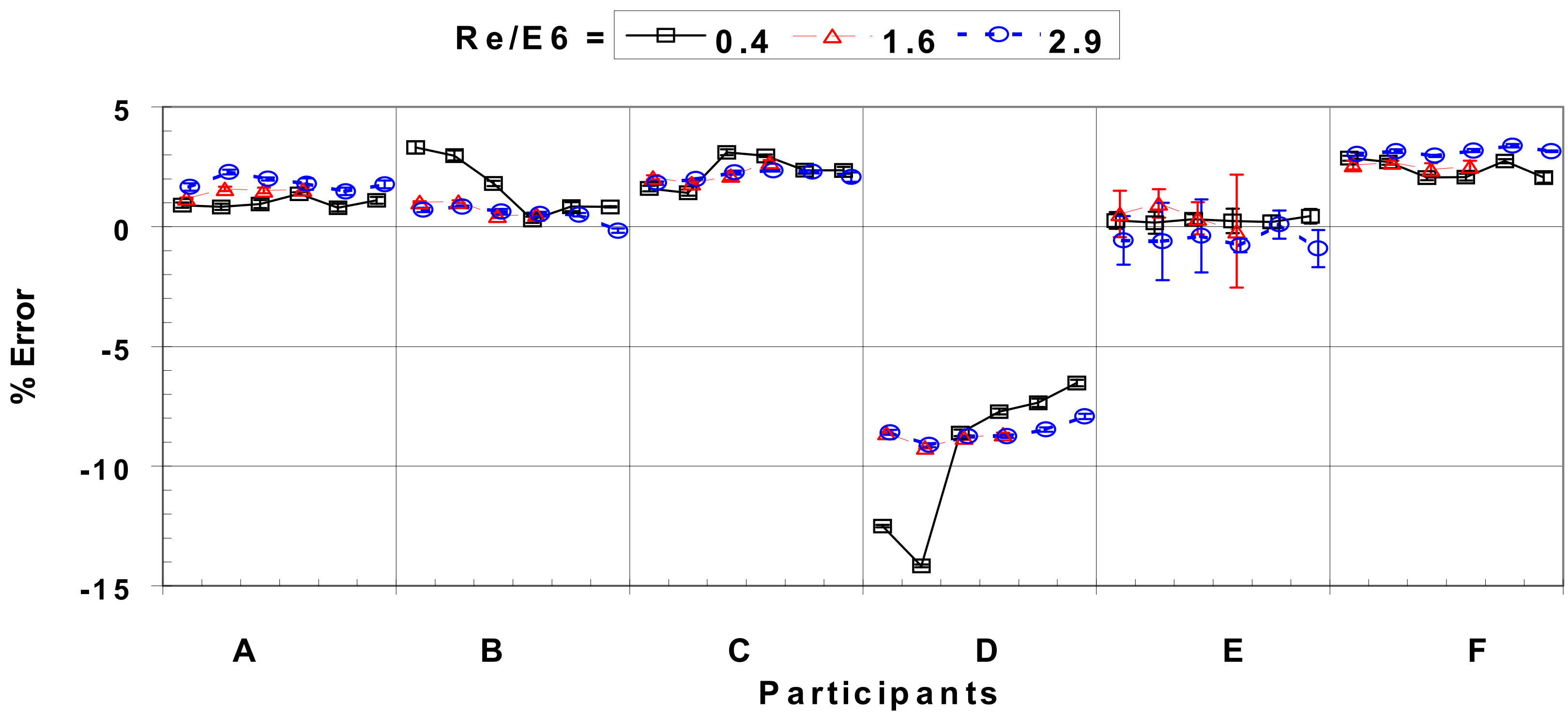


Figure 14(a). Mean Value and Repeatability Results for Each of the Six Tests for All Flow Rates. Values plotted are averages of the five successive error assessments in each test condition relative to the NIST gravimetric standards; error bars show repeatability as defined as one standard deviation of these five successive error assessments about their mean value. The six results sequentially plotted, left-to-right, for each participant and for each flow are, respectively, T1 to T6. As planned, there are no T5 and T6 data for Re=1.6E6.

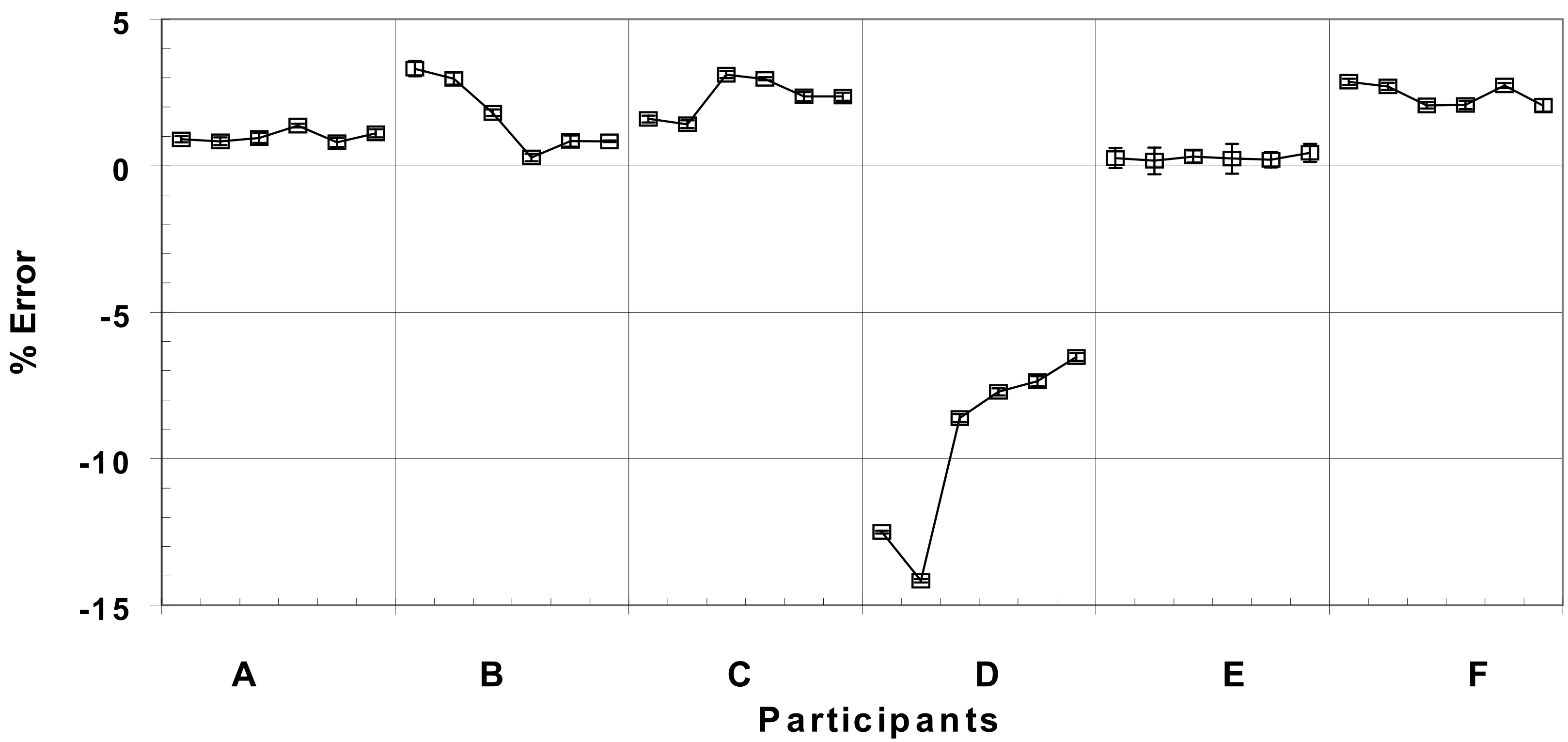


Figure 14(b). Mean Value and Repeatability Results for Each of the Six Tests for Re=4E5. Error bars show repeatability as defined as one standard deviation of the five successive error assessments in each test relative to the NIST gravimetric standards about their mean value. The six results sequentially plotted, left-to-right, for each participant are , respectively, T1 to T6.

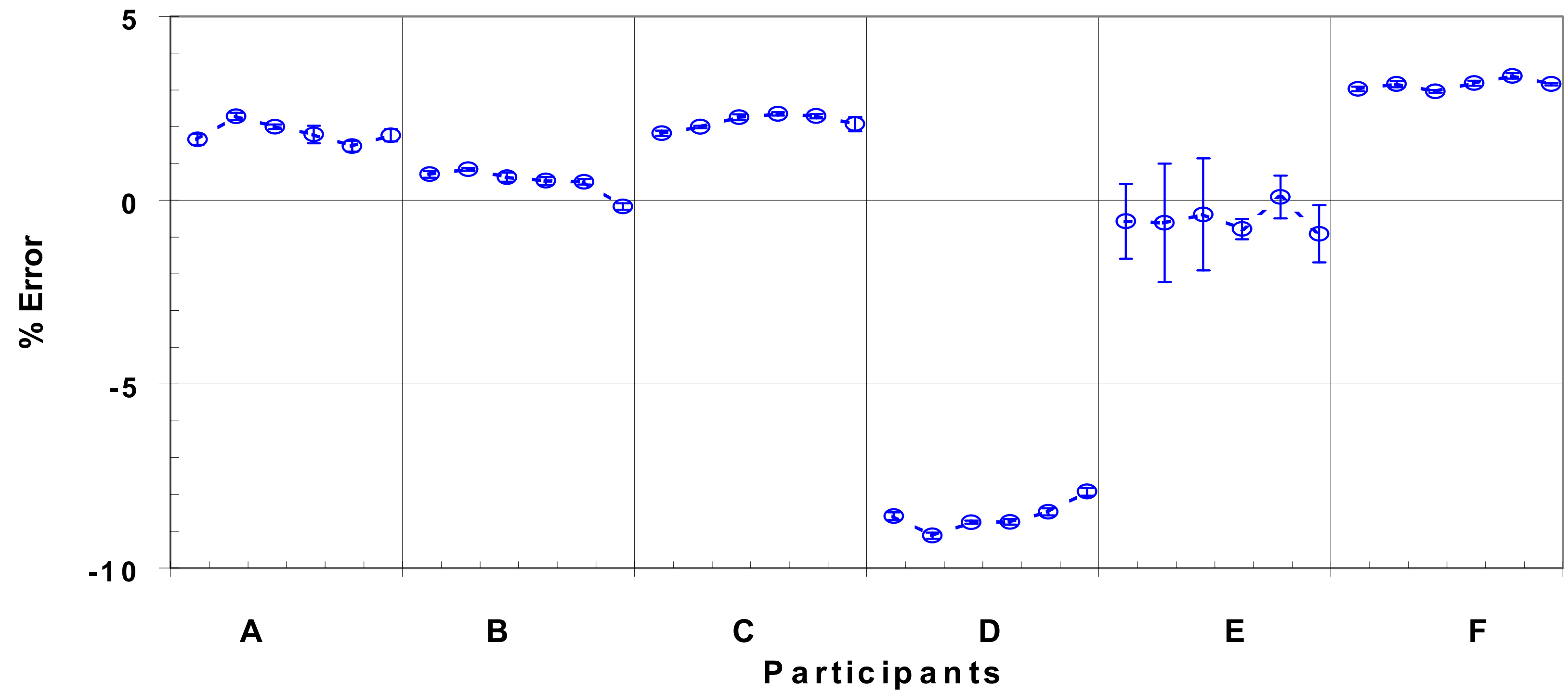


Figure 14(c). Mean Value and Repeatability Results for Each of the Six Tests for Re=2.9E6. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean value. The six results sequentially plotted, left-to-right, for each participant are, respectively, T1 to T6.

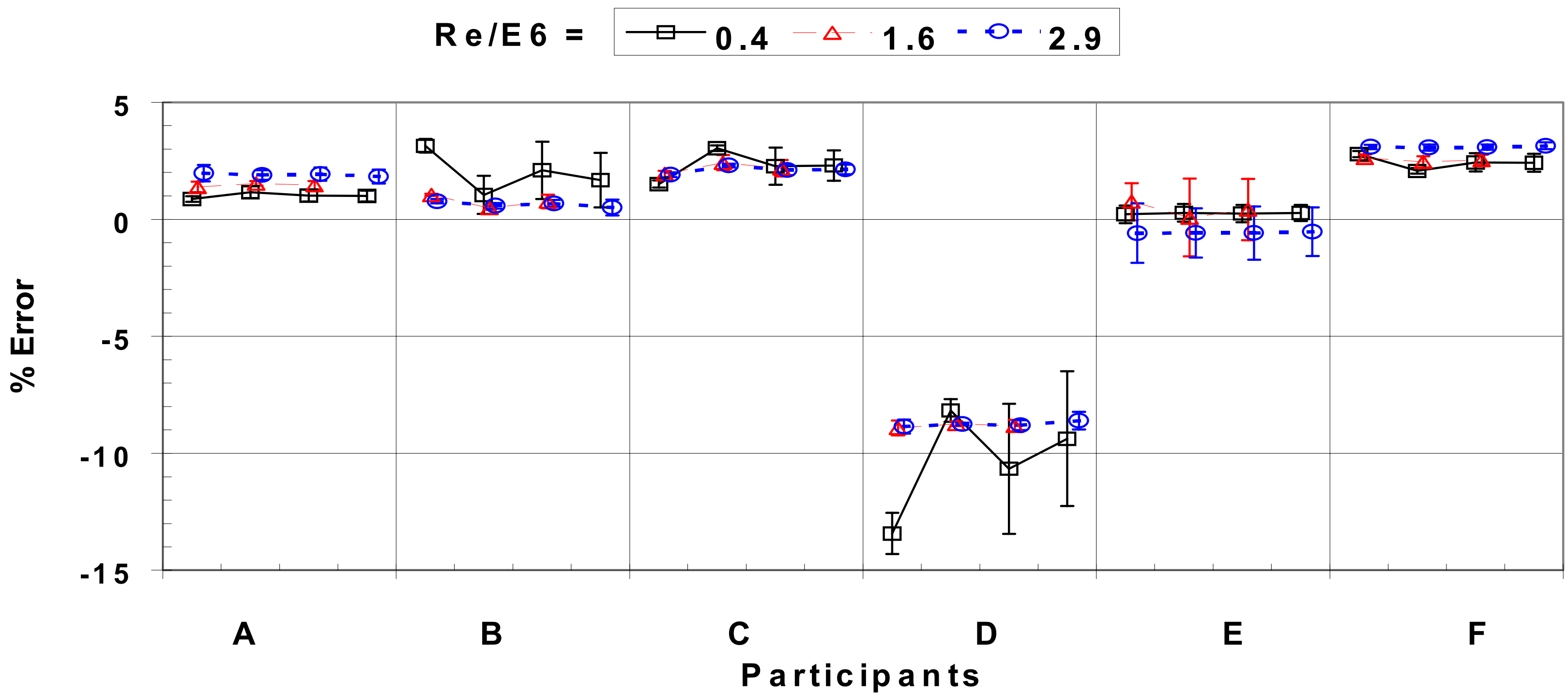


Figure 15. Mean Value and Reproducibility Results for Each Participant for All Flow Rates. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4; T1-4 are for the 20 values in Tests 1-4; and T1-6 are for the 30 values in Tests 1-6. These four results sequentially plotted, left-to-right, for each participant and for each flow are, respectively, T1-2, T3-4, T1-4, and T1-6. It is noted that there is no T1-6 for Re=1.6E6. Respective error bars show reproducibility as defined as one standard deviation about these averages.

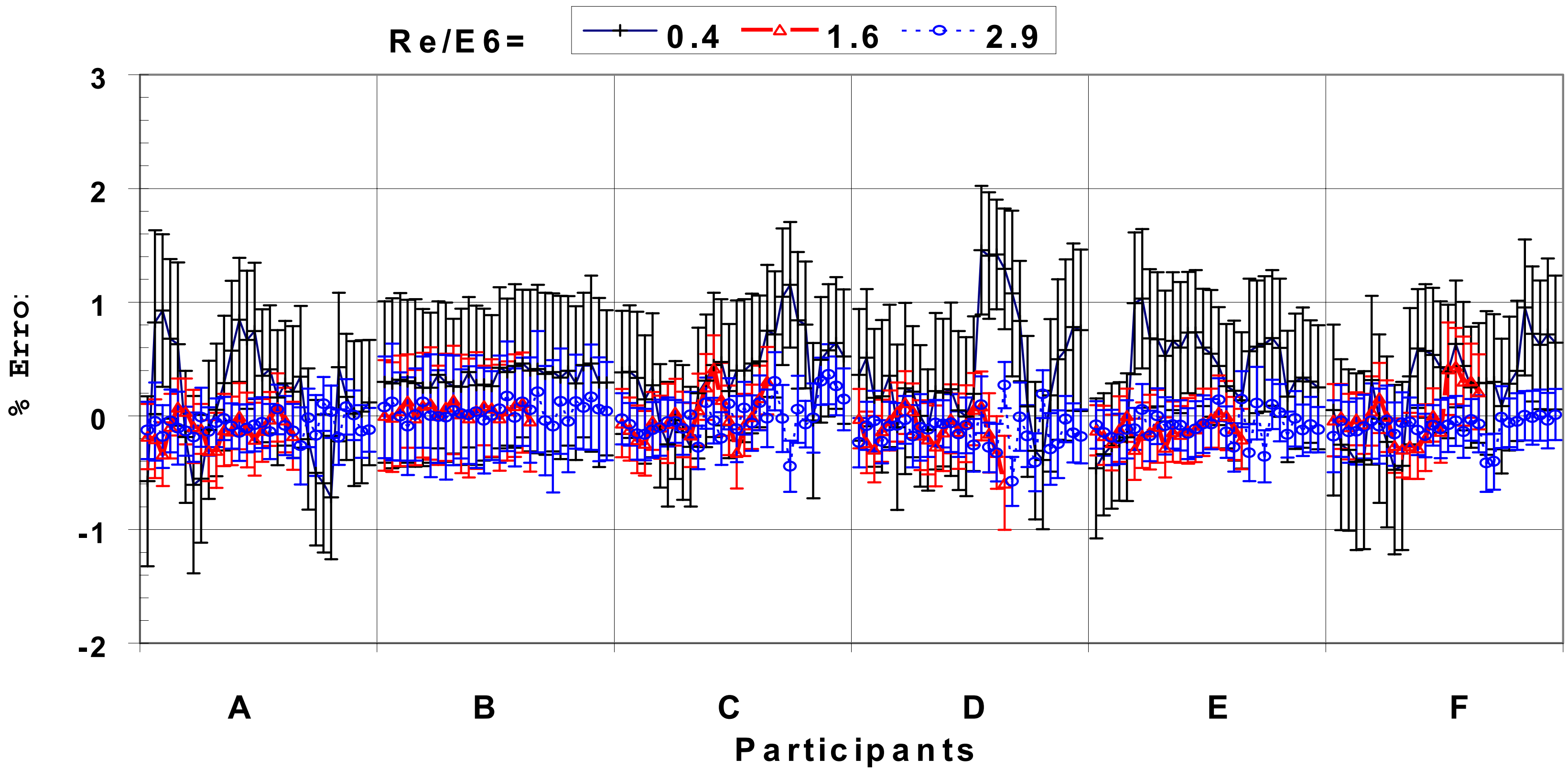


Figure 16. Mean Value Results for the In-Line Ultrasonic Flow Meter through All of the Participants' Tests Expressed as a Percentage Difference from the NIST Gravimetric Standards Result. It is noted that there is no data for T5 or T6 for Re=1.6E6. Error bars show one standard deviation of the time-varying meter indication about its temporal mean value during each timed-collection.

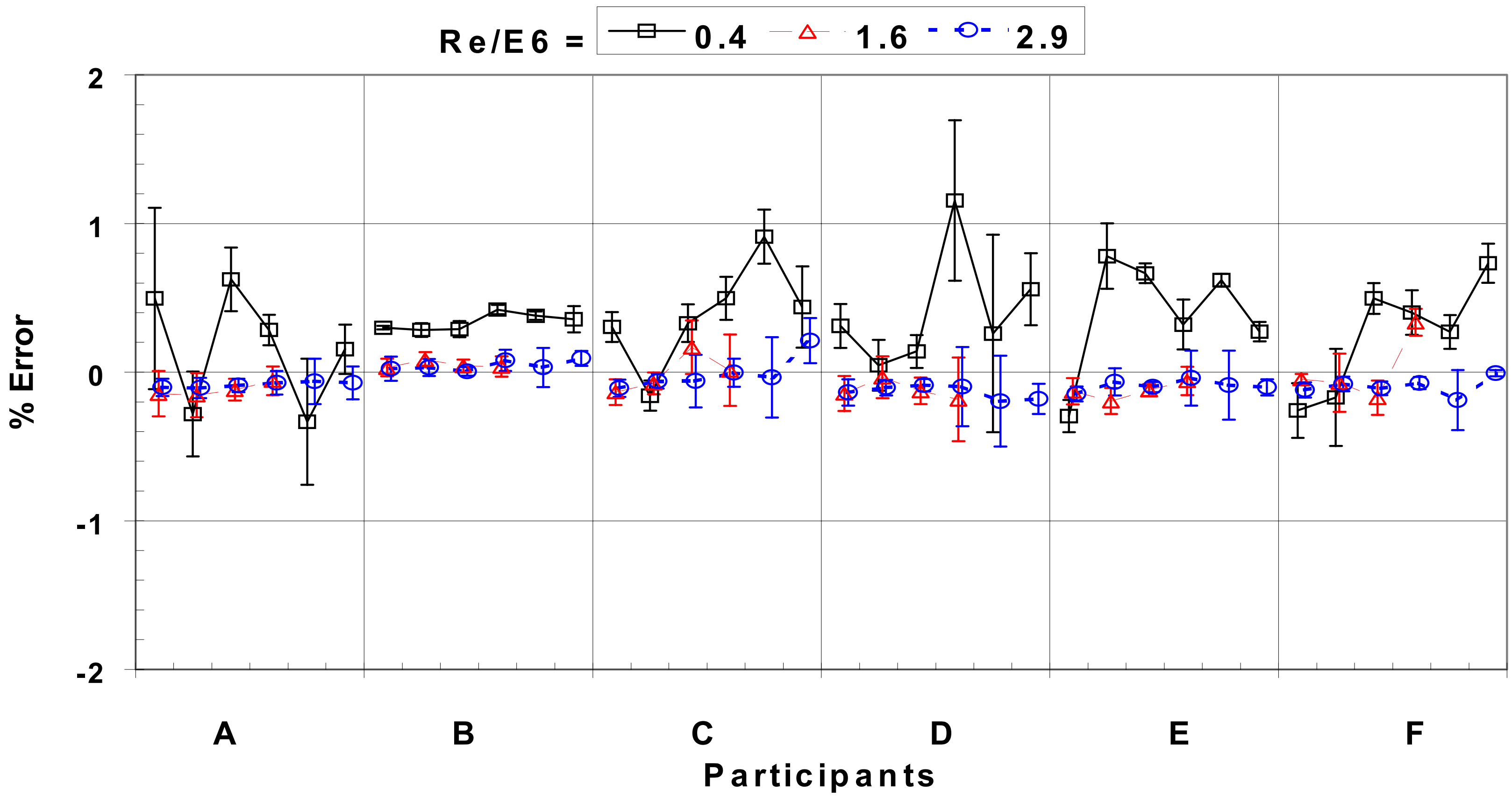


Figure 17. Mean Value and Repeatability Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During Each Participant's Test. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean value. The six results sequentially plotted, left-to-right, during each participant's test and for each flow are, respectively, T1 to T6. It is noted that there is no T5 and T6 data for Re=1.6E6.

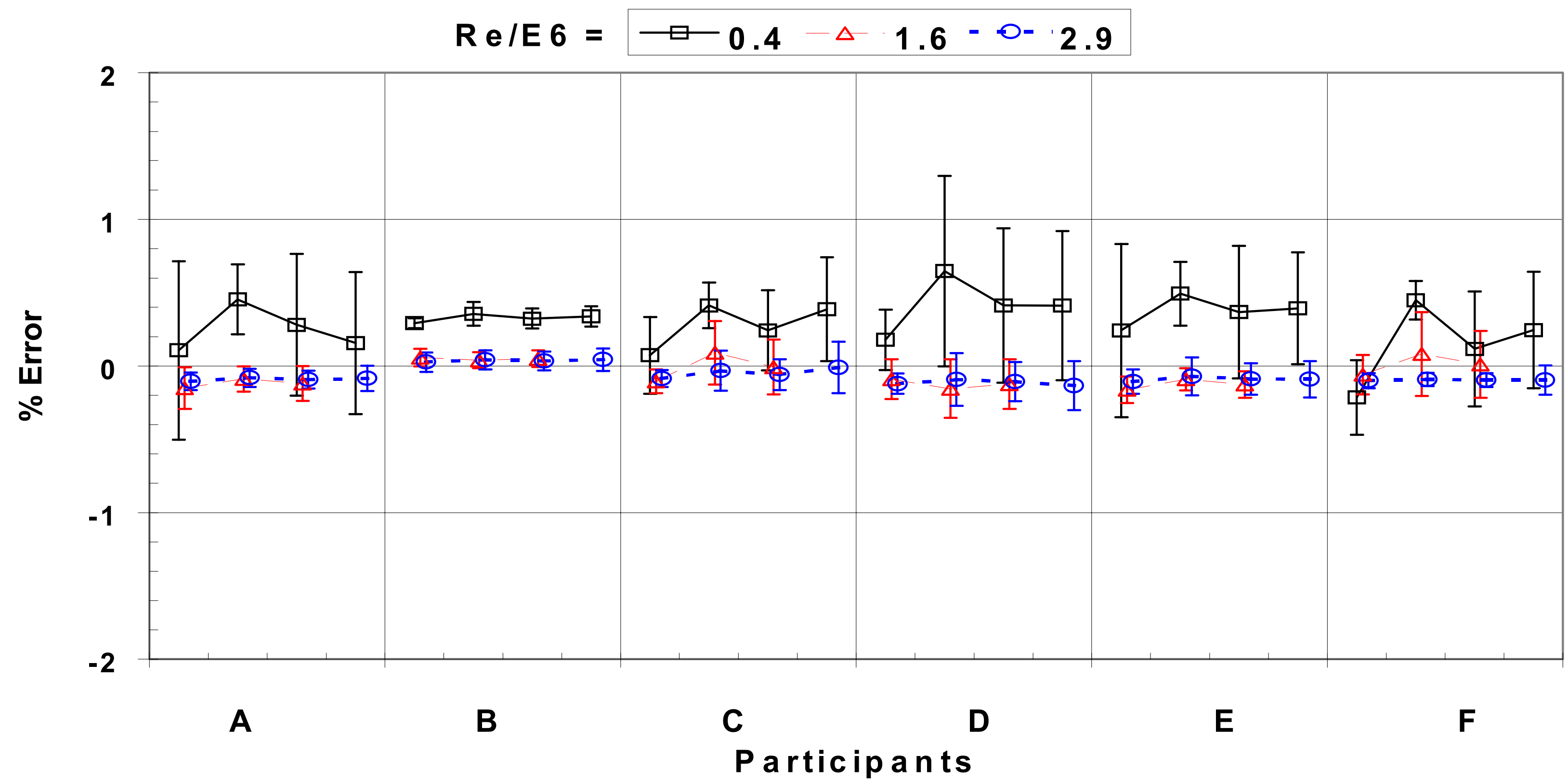


Figure 18. Mean Value and Reproducibility Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During Each Participant's Test. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4, respectively; T1-4 are for the 20 values in Tests 1-4; and T1-6 are for the 30 values in Tests 1-6. These four results sequentially plotted, left-to-right, for each participant and for each flow are, respectively, T1-2, T3-4, T1-4, and T1-6. It is noted that there is no T1-6 for Re=1.6E6. Respective error bars show reproducibility as defined as one standard deviation about these averages.

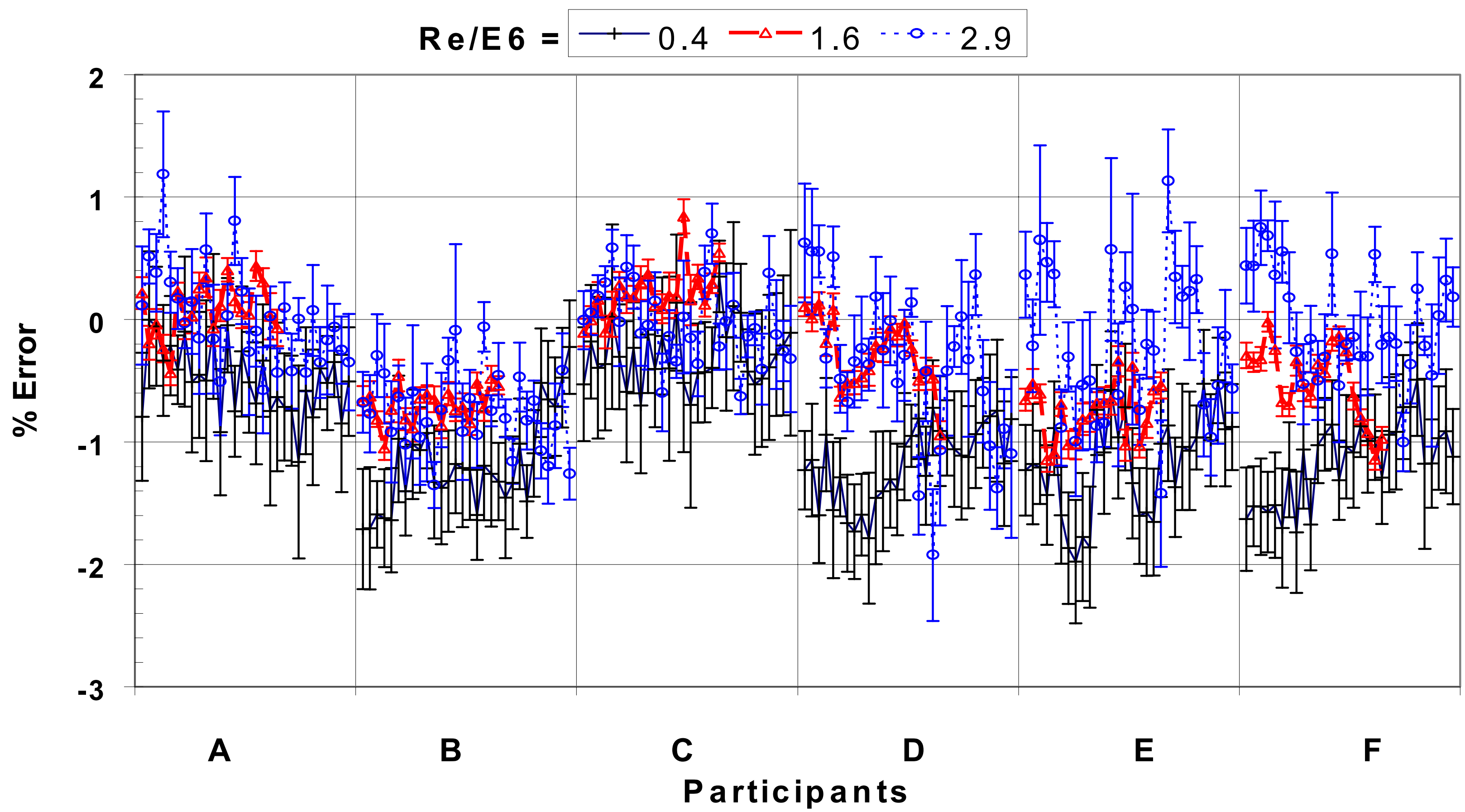


Figure 19. Mean Value Results for the In-Line Magnetic Flow Meter Through All of the Participants' Tests Expressed as a Percentage Difference From the NIST Gravimetric Standards Result. It is noted that there is no data for T5 or T6 for Re=1.6E6. Error bars show one standard deviation of the time varying meter indication about its temporal mean.

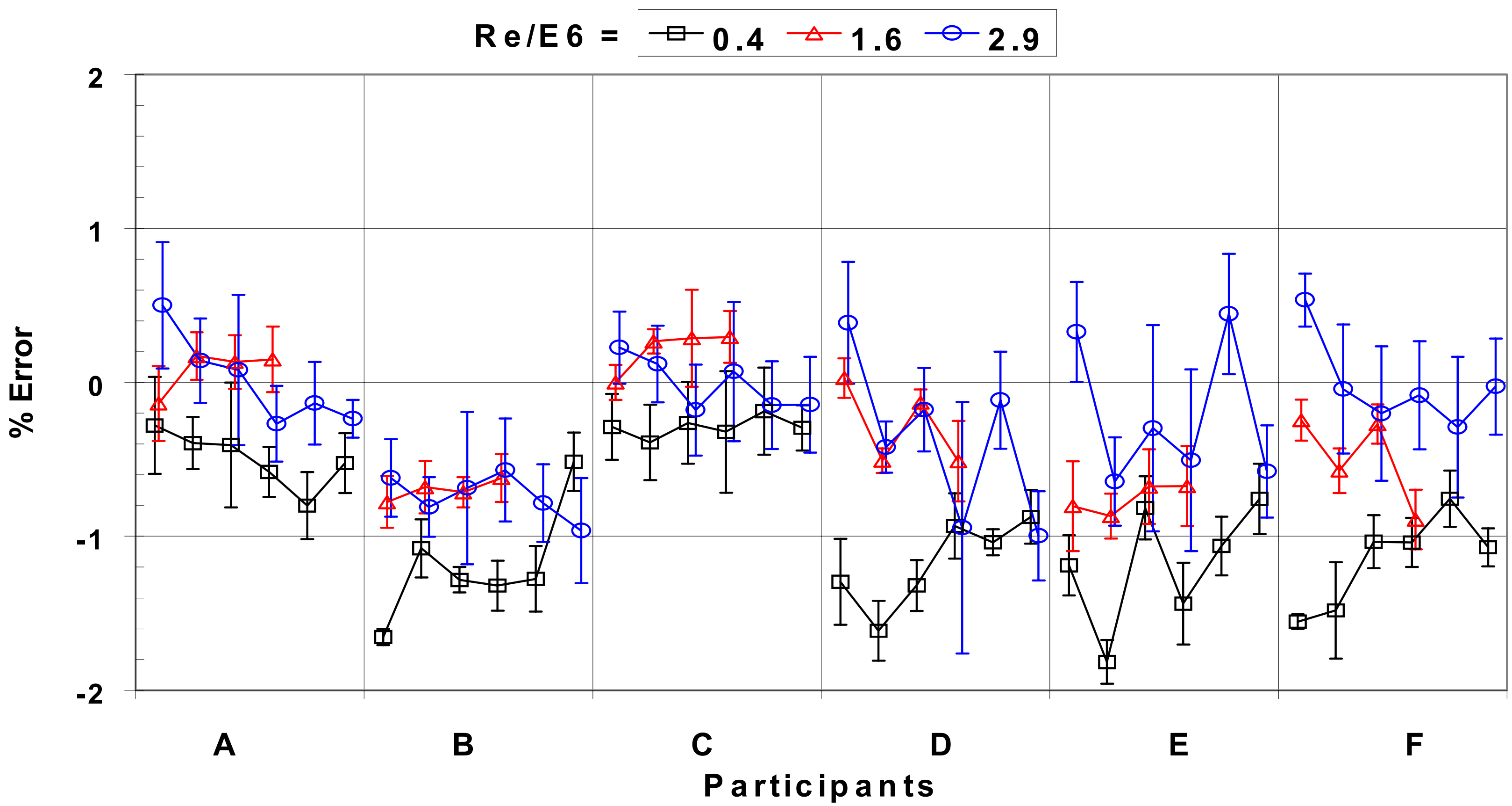


Figure 20. Mean Value and Repeatability Results for the In-Line Magnetic Flow Meter for All Flow Rates During Each Participant's Test. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean value. The six results sequentially plotted, left-to-right, during each participant's test and for each flow are , respectively, T1 to T6. It is noted that there is no T1-6 data for Re=1.6E6.

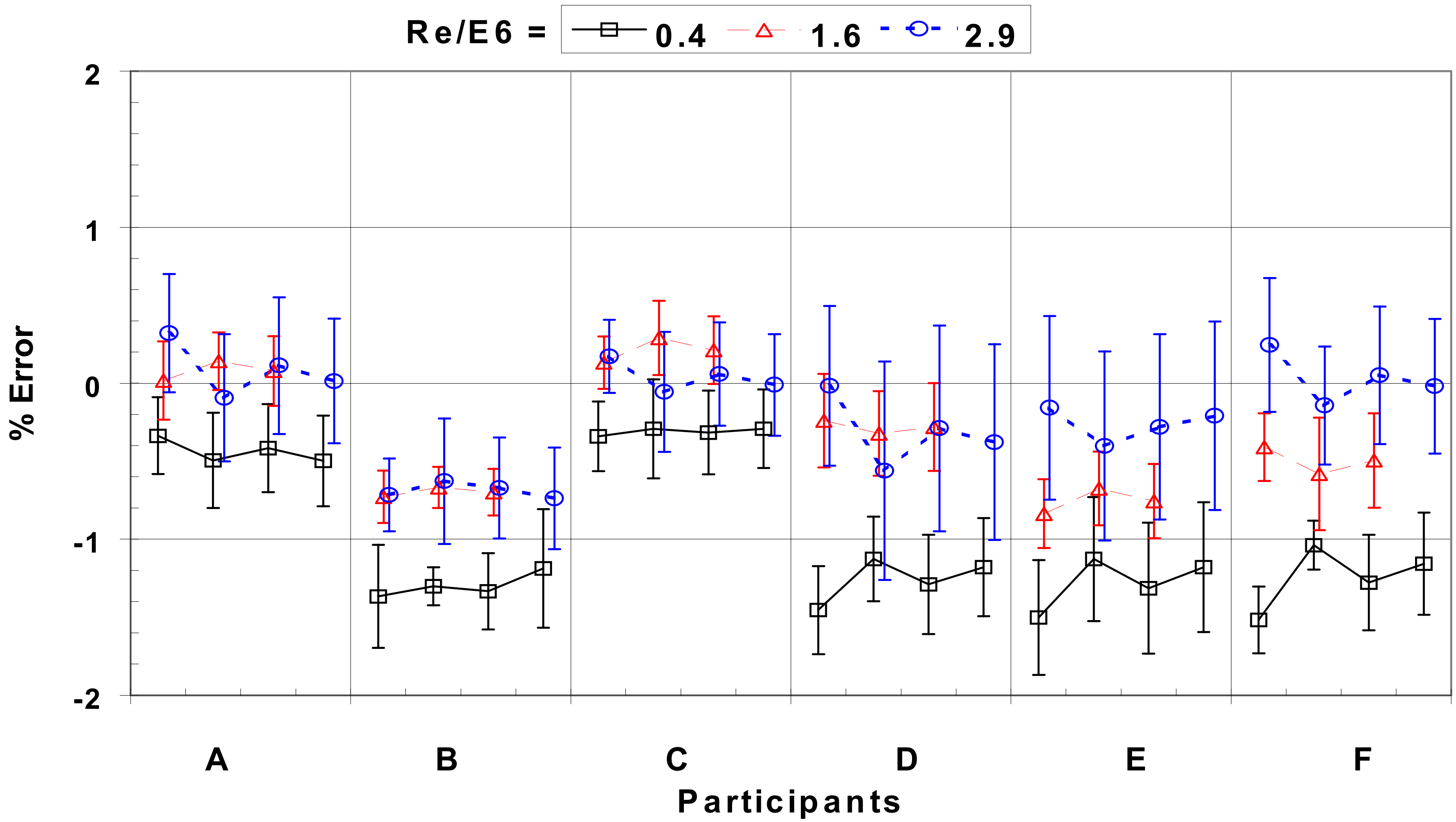


Figure 21. Mean Value and Reproducibility Results for the In-Line Magnetic Flow Meter for All Flow Rates During Each Participant's Test. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4, respectively; T1-4 are for the 20 values in Tests 1-4; and T1-6 are for the 30 values in Tests 1-6. These four results sequentially plotted, left-to-right, for each participant and for each flow, are, respectively, T1-2, T3-4, T1-4, and T1-6. It is noted that there is no T1-6 for Re=1.6E6. Respective error bars show reproducibility as defined as one standard deviation about these averages.