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NIST's Ultrasonic Technology Assessment Program to Improve Flow Measurements

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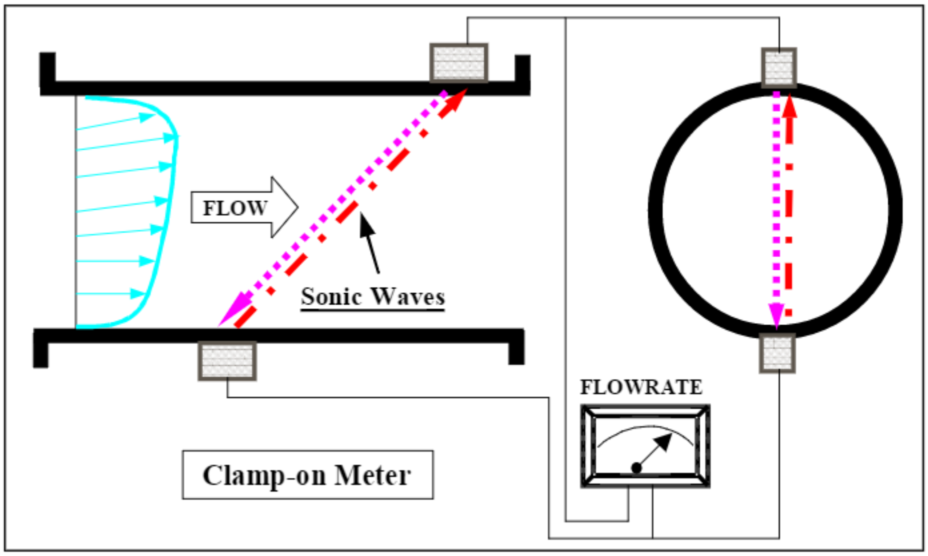

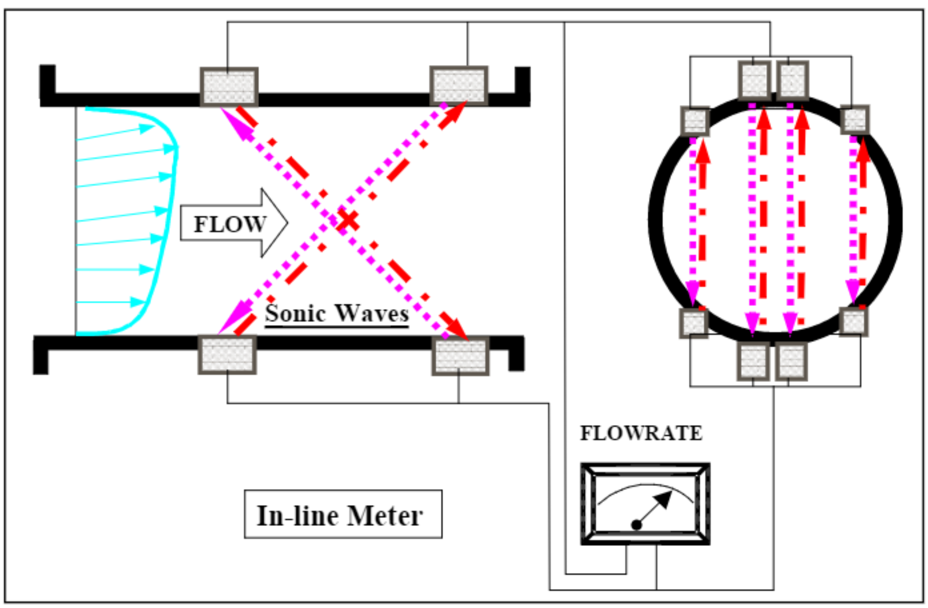

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NIST's Ultrasonic Technology Assessment Program to Improve Flow Measurements

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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

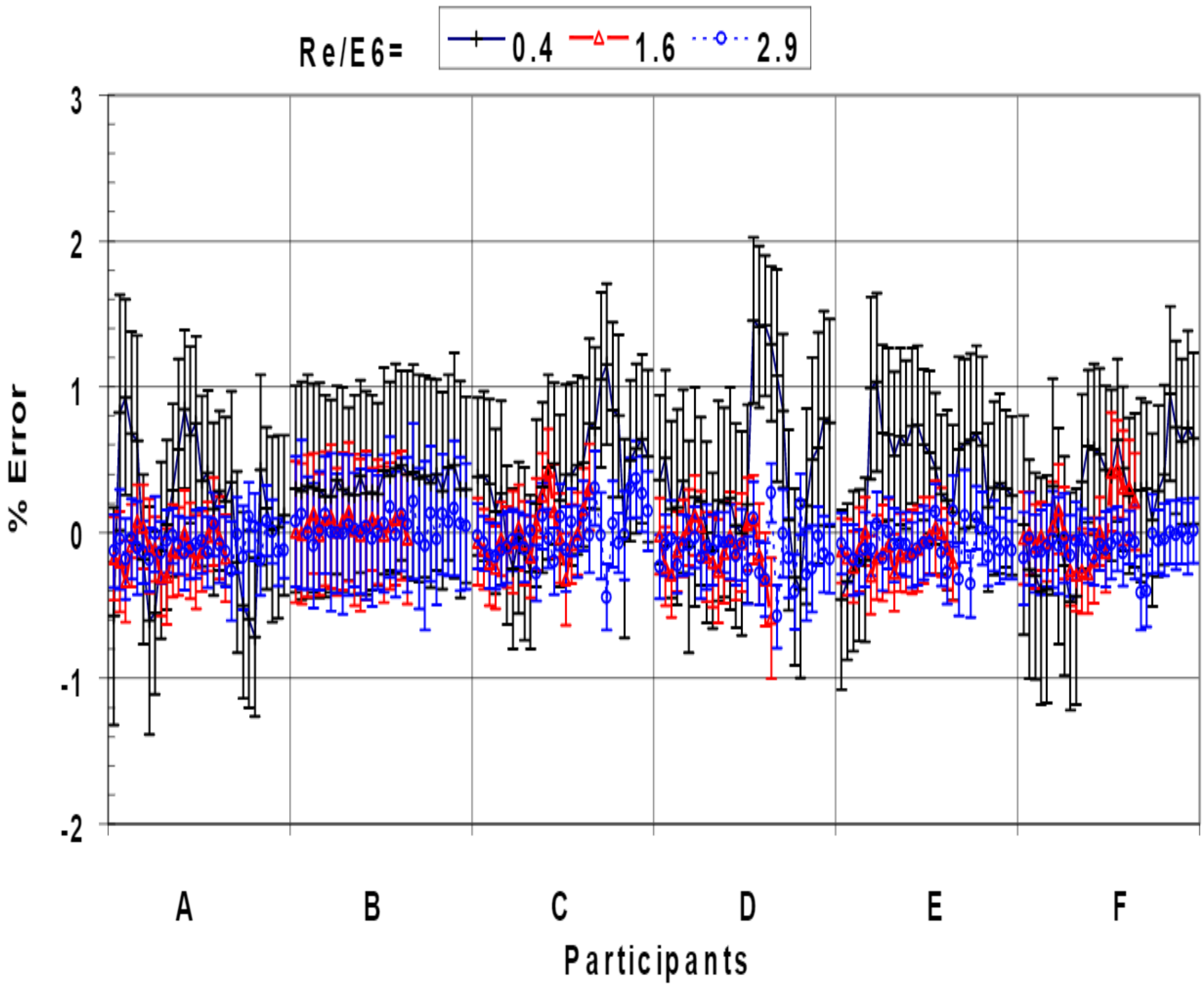

Figure 16. Mean Value Results for the In-Line Ultrasonic Flow Meter through All of the Participants' Tests Expressed as a Percentage Difference from the NIST Gravimetric Standards Result. It is noted that there is no data for T5 or T6 for Re=1.6E6. Error bars show one standard deviation of the time-varying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

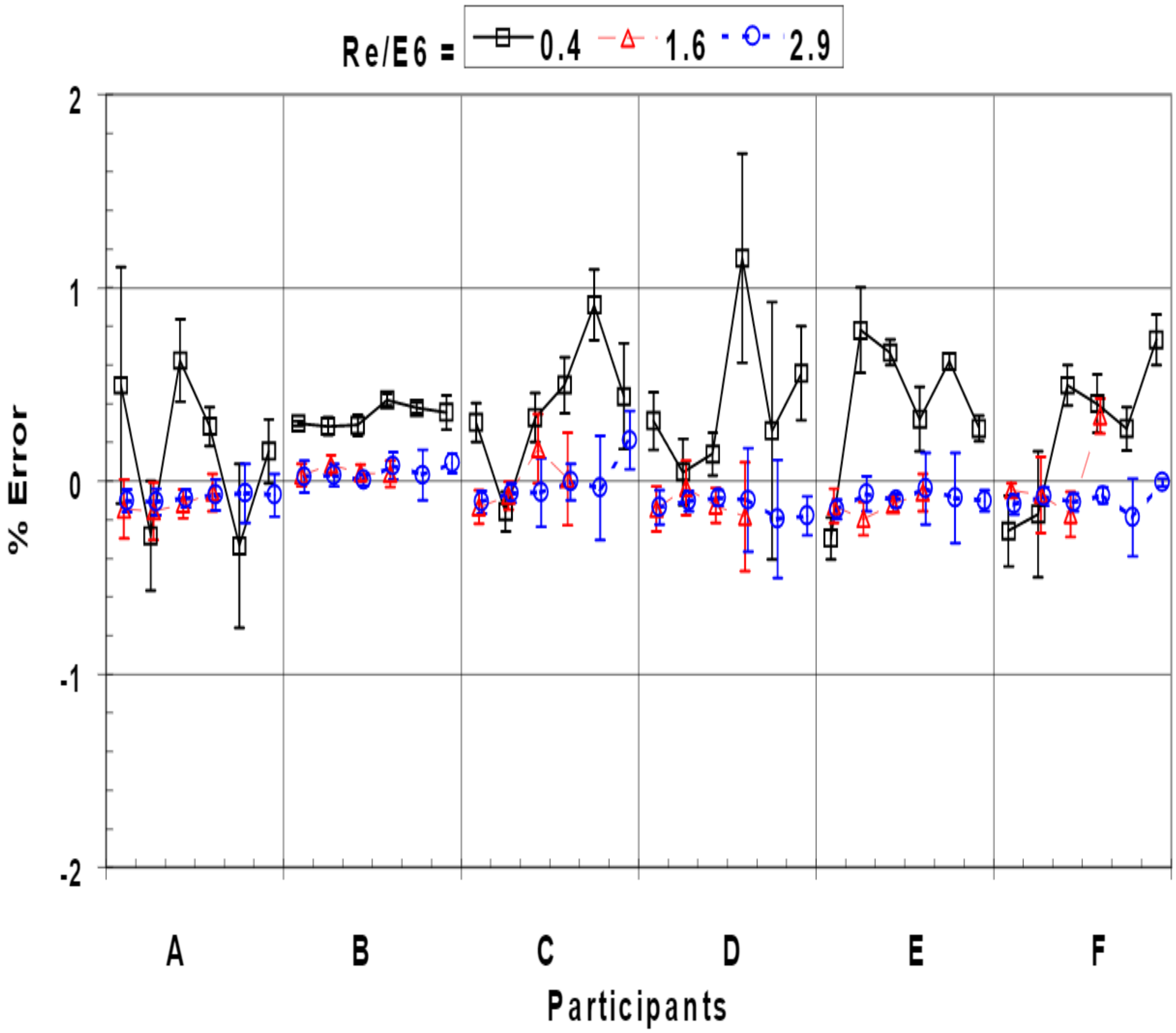

Figure 17. Mean Value and Repeatability Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During Each Participant's Test. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean 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.

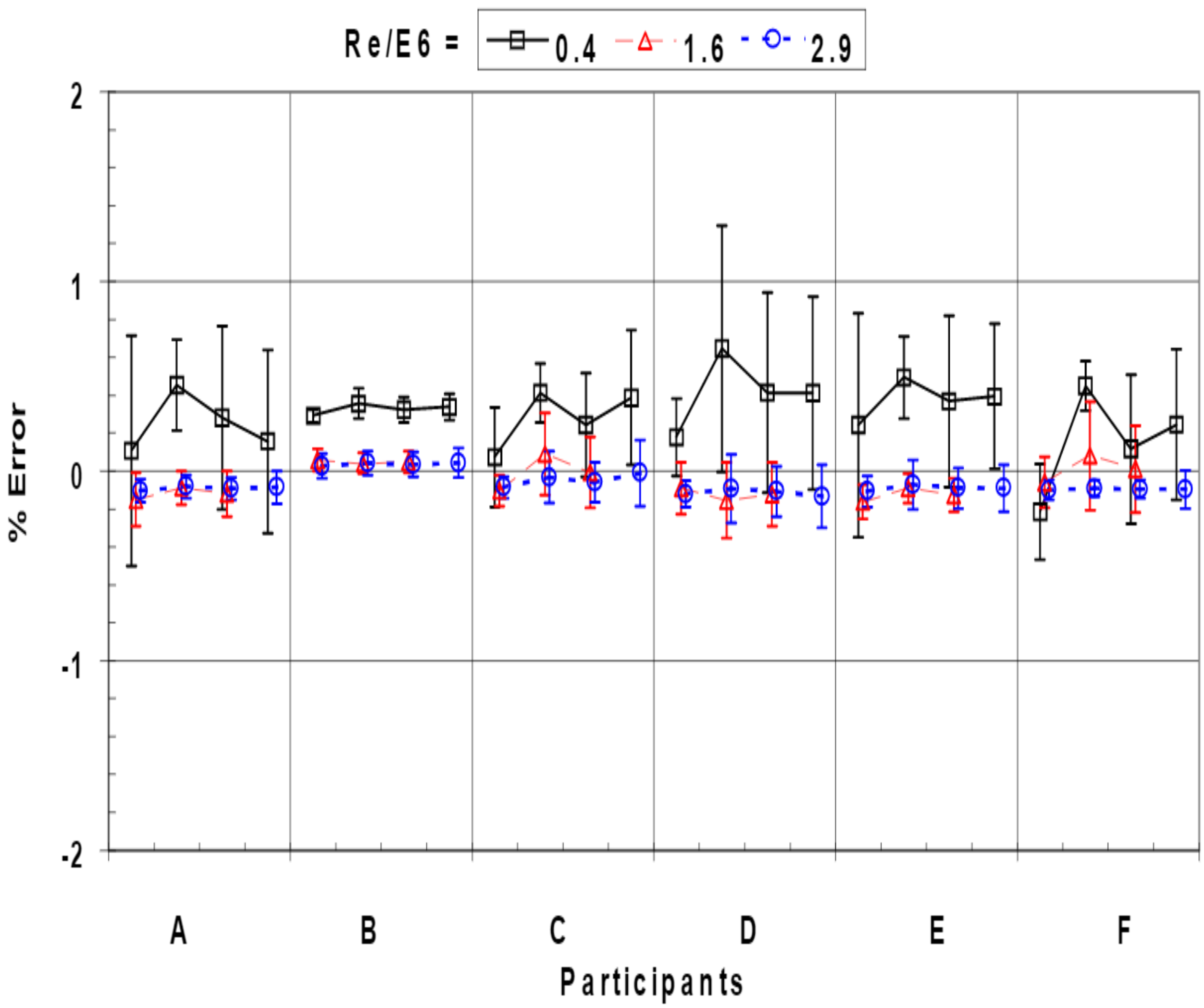

Figure 18. Mean Value and Reproducibility Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During Each Participant's Test. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4, respectively; T1-4 are for the 20 values in Tests 1-4; 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.

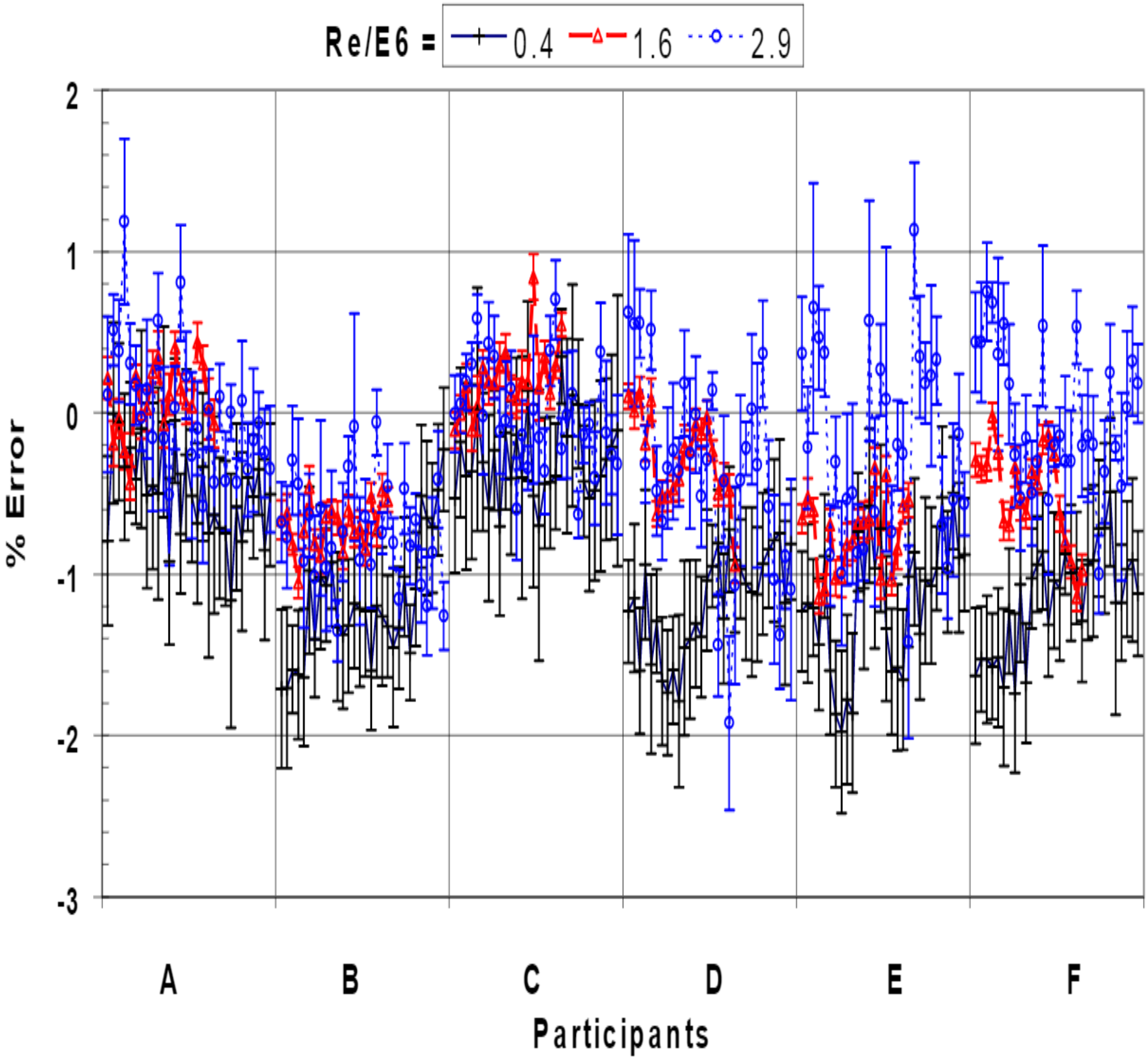

Figure 19. Mean Value Results for the In-Line Magnetic Flow Meter Through All of the Participants' Tests Expressed as a Percentage Difference From the NIST Gravimetric Standards Result. It is noted that there is no data for T5 or T6 for Re=1.6E6. Error bars show one standard deviation of the time varying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

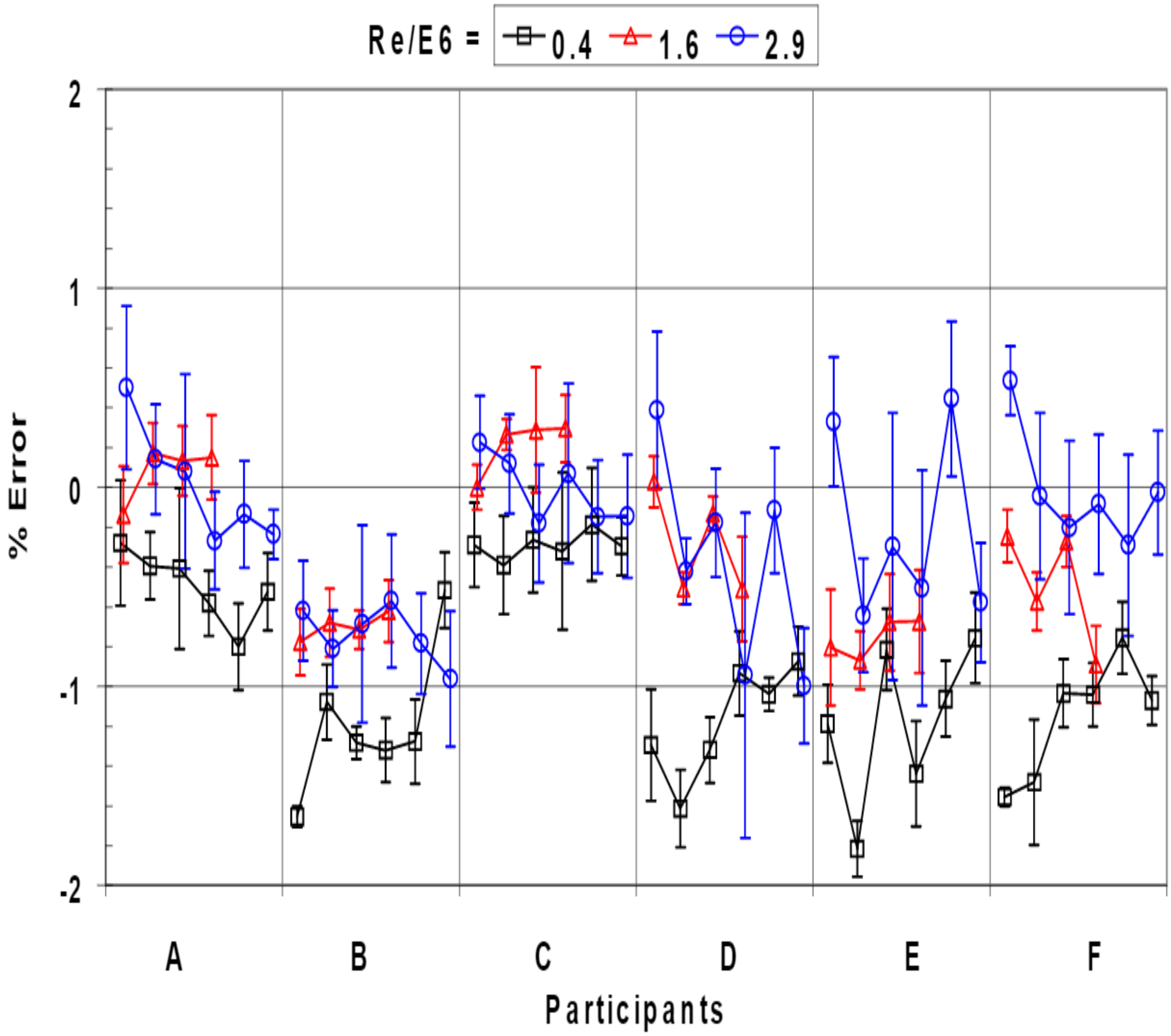

Figure 20. Mean Value and Repeatability Results for the In-Line Magnetic Flow Meter for All Flow Rates During Each Participant's Test. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean 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.

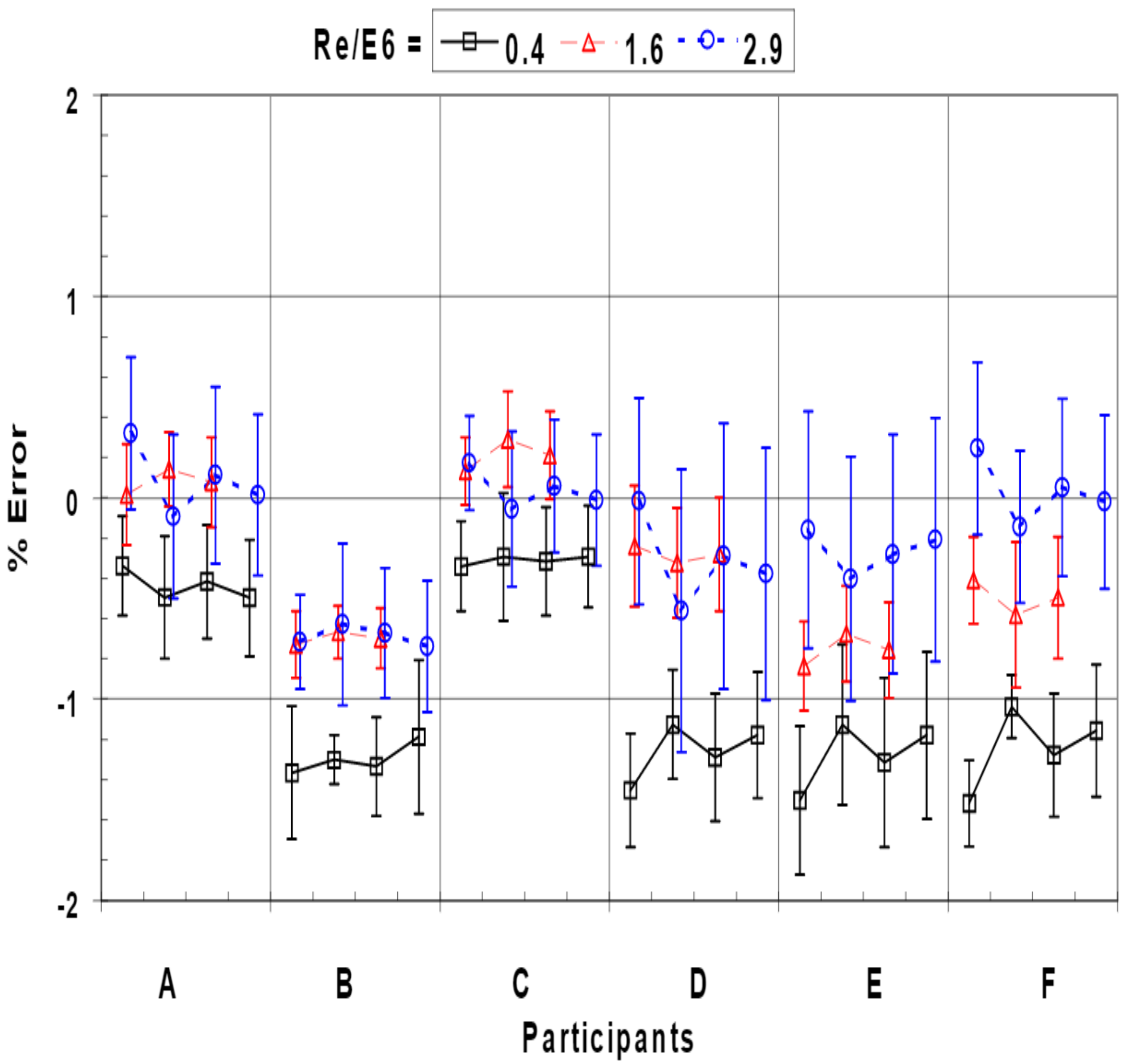

Figure 21. Mean Value and Reproducibility Results for the In-Line Magnetic Flow Meter for All Flow Rates During Each Participant's Test. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4, respectively; T1-4 are for the 20 values in Tests 1-4; 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.