ULTRASONIC TECHNOLOGY: PROSPECTS FOR IMPROVING FLOW MEASUREMENTS AND STANDARDS

T. T. Yeh and G. E. Mattingly
Fluid Flow Group
Process Measurements Division
Chemical Science and Technology Laboratory
National Institute of Standards and Technology
Gaithersburg, Maryland 20899
USA

ABSTRACT
Ultrasonic technology is evolving rapidly. It offers prospects for improving flow measurements, for serving as transfer standards, and possibly for serving as a primary flow standard. This paper describes results from several current NIST projects that have the goal of assessing travel-time ultrasonic flow measurement techniques for their potential in improving flow measurements. These projects include a meter testing program and computer simulations of travel-time techniques in ideal conditions and in measured pipe flows for a range of metering configurations.

Meter test results show that the "as-received" performance of several commercially available, clamp-on, travel-time, ultrasonic flow meters have errors that range from 1% to 3% when measuring high Reynolds number water flows in nearly ideal installation conditions. These errors could be reduced if manufacturers better compensated for pipe flow profile effects using improved software or if they improved the measurement traceability of their meter calibration capabilities to NIST's flow standards. The reproducibilities of most of these units are 1% or better, thus producing conclusions that these meters could attain accuracy levels commensurate with these reproducibilities if these software or calibration improvements are made.

Results also show that these manufacturers have significantly improved: (1) the awkward requirement for a "zero flow" condition to attain satisfactory performance, and (2) the "remove-replace" variations which plagued these types of meters.

Additionally, test results for an in-line, 8-path, travel-time, ultrasonic meter that was set up using only length and time standards showed uncertainties of ±0.2%, or better. These results show that this kind of meter might evolve into a primary standard for flow.

The computer simulations of travel-time metering arrangements provide insight into ways that this technology can improve flow measurements. If it becomes feasible to quantitatively model all the component measurement systems that comprise the ultrasonic metering of a pipe flow using only length and time standards, this technique would be a primary standard at some specified uncertainty. This would greatly expand the capability of primary flow standards, and it would make flow measurements traceable to national standards.

INTRODUCTION
The objectives of this study are to improve our understanding of ultrasonic flow measurement, to assess its potential for improving flow measurements, and to test the performance of selected travel-time meters, [1,2][1]. We tested several meters and used computer simulations to study installation effects. This paper focuses on prospects for dual-sensor, travel-time ultrasonic techniques applied to high Reynolds number

[1] Square bracketed integers refer to references given below.

pipe flows in water. Our meter installation conditions approached "ideal" in order to assess optimal performance characteristics. In this paper, we describe results from a recent testing program for travel-time flow meters and we use computer simulations to understand the effects of pipe flows on the performance of this type of meter, [1].

TESTING PROGRAM

NIST devised a program to test the performance of a number of several commercially available, clamp-on, travel-time flow meters. Details are given in [1]. The meters were installed on pipes both with and without a "zero flow" condition. The tests also determined the effects of removing these meters from the pipes and re-installing them. The "remove-replace" tests were done when the mounting rails were left clamped to the pipe and the sensors were taken off, and when both sensors and rails were removed and replaced. To minimize the meter performance variation associated with installing these clamp-on units, the manufacturers performed these tasks. The meter manufacturers that participated are listed alphabetically in the Acknowledgment.

Tests were done using 250 mm dia., schedule 40, 304 stainless steel pipe having 150 lb flanges. The Reynolds number ranged from 4E5 to 3E6. The coordinate system used is right-handed with the origin on the pipe centerline at the entrance to the 250 mm dia. 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. The pipe flow characteristics in the test pipe were measured using laser Doppler velocimetry (LDV) [5]; results are shown in Figure 1 for the highest and lowest flows tested along horizontal and vertical diameter traverses in the test pipe where the meters were installed. Figure 1 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, [6,7].

The NIST flow standards were used to determine the flow rates in these tests. These standards use static gravimetric techniques that have a quoted expanded uncertainty of 0.12%, using a coverage factor of 2, [1, 3 and 4]. These standards were used to assess meter indications that were averaged during the 40 to 140 second collection intervals used for the gravimetric standards. To obtain real-time data for the pipe flow during the tests, an in-line, travel-time, ultrasonic flow meter was installed downstream of the meter test section. This unit was a Fisher Precision Systems, Inc., Model 2502[1] having 8 chordal paths. The results from this ultrasonic unit are presented below because they contribute significantly to our conclusions that ultrasonic techniques have great potential for improving flow measurements.

The time-averaged results for the clamp-on meters and the in-line ultrasonic flow meter were assessed using the NIST standards. The deviations of the rapidly recorded meter outputs from the in-line ultrasonic meter and the clamp-on meters were expressed as standard deviations and are presented graphically using error bars about their temporal mean values. Further averaging quantified the repeatability and reproducibility of both the in-line and participating meters, as described below.

Initial tests quantified clamp-on meter performance without and then with a "zero flow" condition. To quantify the repeatability of the 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 rate test sequence was run with nominal Reynolds numbers of 4E5, 1.6E6, and 2.6E6. Five gravimetric determinations of flow rate were done at each Reynolds number. Once the three flow rate sequence was completed, the flow was stopped. A second sequence was done without alteration of the meter.

The average of the recorded participating meter results taken during the gravimetric collection was compared to each of the five static gravimetric determinations of flow rate with NIST's standards. 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 defined to be the meter

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

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 defined to be the meter reproducibility for the flow 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 will indicate the corresponding results for the "zero-flow" start condition.

To quantify the effects of removing then re-installing the meters, 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. The tests designated T6 show the effects of removing and replacing both the sensors and rails. 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. The data set for each meter tested 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 remove-replace tests.

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, [8]. Our simulation results shown in Figure 2 indicate that if travel-time ultrasonic flow meters use typical paths through the pipe center from transmitting and receiving sensors and if the pipe flow distribution is assumed to be uniform, then positive errors will occur, [8]. These errors will range from 5% to 6.5% of the true value in our flow test range, depending upon which model for the ideal flow distribution is selected. These errors depend on Reynolds number, pipe roughness, inlet flow conditions, distance from the inlet, etc. For most fully developed pipe flow distributions, these distributions decrease monotonically with Reynolds number. Note that the Gilmont distribution was developed for lower Reynolds numbers less than 1E5, [9]. We also note that meters that are properly compensated for these effects need to have the proper negative trend with increasing Reynolds number.

Meter simulations were done using the profile measurements shown in Figure 1, assuming negligible axial gradients. Results are given in Figure 2. The data denoted LDV-H and LDV-V show the errors that would occur if the meter were installed horizontally and vertically, respectively, and if its readings were interpreted using the assumption that the pipe flow profile was 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 1(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, [6,9-11]. We estimate the LDV results shown in Figure 1(a) to be within 1% of the true values, and conclude, therefore, that these simulation results are due to the LDV values lying, for the most part, below counterparts in the Bogue & Metzner distributions in Figure 1(a). These simulation results also show decreasing errors with Reynolds number for both horizontal and vertical profiles. 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 DISCUSSION OF METER TESTS

Figure 3 plots error assessment data for the clamp-on units for all 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 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 mean of the five time-averaged differences at each test condition. These error bars represent the "single reading" imprecision of the meter in these conditions. Excluding the meters with the largest percentage error (D), and the largest time-averaged deviations from means (E), these results show errors that are predominately positive, ranging from approximately +1% to +3%, with most values in the range from +2% to +3%. For these meters, standard deviations of time-averaged differences ranged up to 0.5%. These manufacturers are compensating in part for profile effects. If they had assumed a uniform profile at Reynolds numbers of 4E5 and 3E6, errors of +5% and +4% would have resulted, see Figure 2. If these manufacturers had used Bogue and Metzner or Reichardt profile distributions to produce their metering results, the errors would have been –0.5% to –1.7%.

Figure 4 presents mean values and repeatability results for all 6 clamp-on meter tests. The data plotted are the means of the five successive error assessments obtained in each of the six tests, denoted T1 through T6. Most of the data range from –1% to +3%; the worst case error is –14%, but this occurred only for manufacturer D. Error bars quantify repeatability, which is defined here as one standard deviation of the mean of the five successive error values at each test condition. Repeatabilities range from ±0.1% to ±0.2% for most of these manufacturers; the worst case is ±2%, but this occurred only for meter E. Additionally, Figure 4 shows error trends that, for several of these meters, are either constant or increase with Reynolds number, namely A, F, and for some conditions, C. This contrasts with the negative trends expected from the simulation results shown in Figure 2. Therefore, we conclude that both flow profile compensation and its trend with Reynolds number need to be reconsidered by these manufacturers.

Figure 5 presents mean values and reproducibility results for all clamp-on meters for all flow rates. Reproducibilities are here defined as the standard deviations of the mean for: (1) the ten values at each flow in tests T1 and T2, where no “zero-flow” condition was allowed before testing, and in tests T3 and T4, where a zero flow condition was used, (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 6 shows the results of these tests mostly range from +0.5% to +3%; the worst case is –13.5%, but this occurred only for meter D. Reproducibilities range from ±0.1 to ±3%, but three meters 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 meters could attain performance levels ±1%, or better.

Figures 6-8 present error assessment results for the in-line ultrasonic flow meter as obtained during the six tests of the clamp-on meters. Figure 6 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. This unit also assessed, in real time, the pipe flow distributions in these test flows using its four chordal planes of measurement; results are compatible with the data shown in Figures 1(a) and (b). Figure 7 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 tests of meter B a minor software change was made to enhance its noise suppression capabilities. Figure 8 gives reproducibilities, with error bars showing one standard deviation of the respective values about their mean. Figure 8 shows 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. From this impressive performance at these higher flows, we conclude that it may be feasible to recognize this meter as 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.

CONCLUSIONS:

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

1) Their errors, as obtained by recording and averaging meter outputs and comparing these to the results from NIST’s gravimetric flow measurement standards, range from +1% to +3% except for the -14% for meter D.
2) Repeatabilities, as defined by the standard deviation of the mean of five successively determined error assessments, range from ±0.1% to ±0.2% except for the ±2% result for meter E.
3) Reproducibilities, as defined by the standard deviations of the mean of error assessments made under a variety of conditions 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 compensate for profile effects; however, the compensations could be improved.

Clamp-on type, travel time ultrasonic technology has progressed very well in improving flow measurement. Concerns regarding "zero flow" set requirements and "remove-replace" variations, dating to the early stages of ultrasonic meter development are no longer valid. If meter buyers are properly trained, they should be able to attain the same performance.

The ultrasonic reference meter used in these tests had errors and repeatabilities of 0.2% or better for the two higher flows This meter was not calibrated by the manufacturer; it was set up using only length and time standards. Its impressive performance at these higher flows indicates that it may be feasible to recognize this meter as a primary flow standard. If this development were to occur, it would extend the capabilities of flow laboratories for establishing and maintaining flow measurement traceability to national standards.

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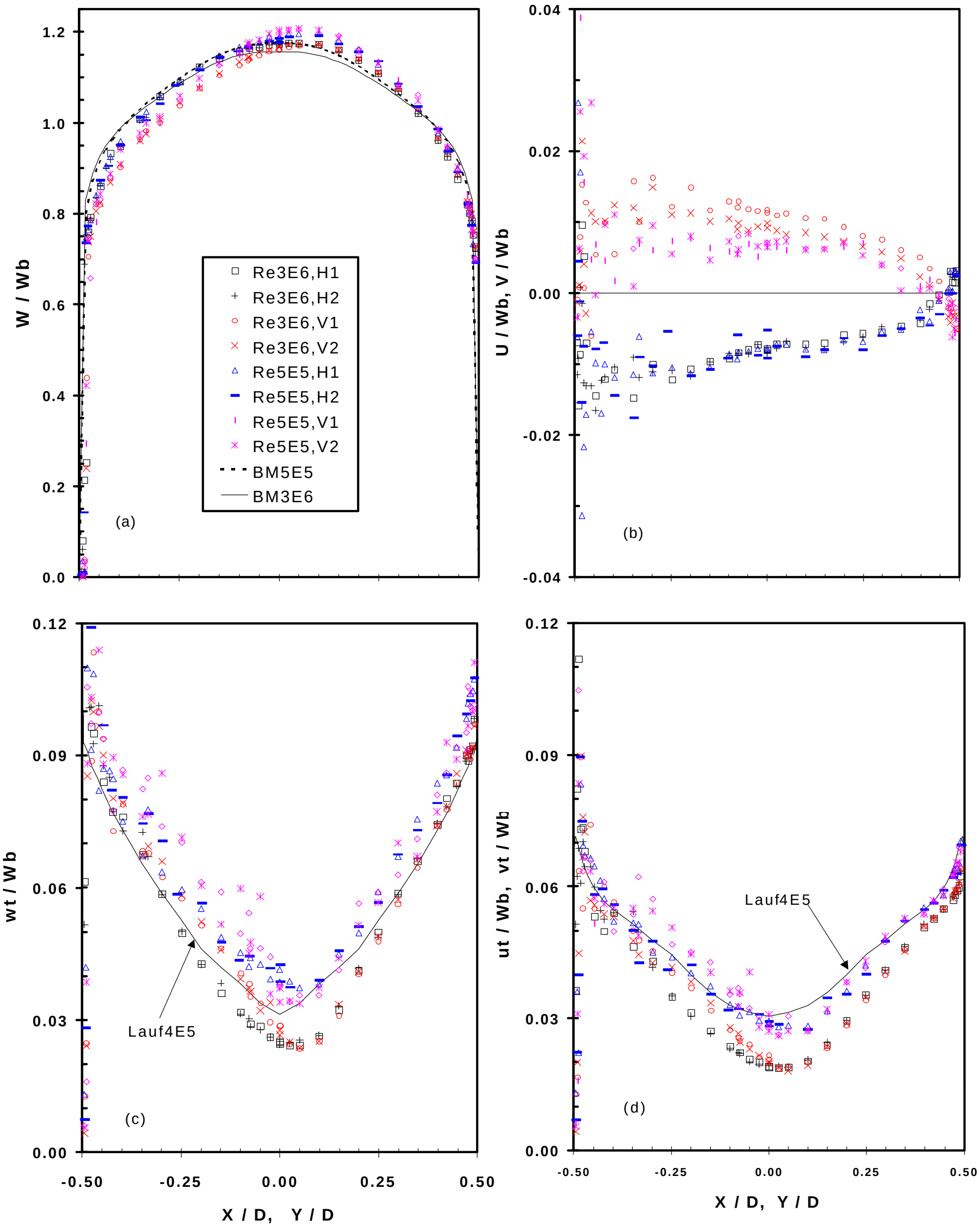

Figure 1. Pipe Flow Characteristics: These LDV results were measured over horizontal and vertical diameters for the lowest and highest flows used for testing. Notations are: W is the mean axial velocity; W_b is the bulk average velocity determined using NIST's Gravimetric Standards; X/D and Y/D are, 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. (a) The lines show the Bogue & Metzner profiles for: Re=3E6, the solid line; Re=5E5, the dashed line. (b) Mean Transverse Velocity Profiles, U and V along the vertical and horizontal diameters, respectively. The zero ordinate denotes the ideal transverse velocity profile. (c) Axial Turbulence Intensity Profiles. wt is the rms of the axial turbulent velocity. The line shows Laufer's measured distribution for the axial component of the turbulence for Re=4.3E5, [7]. (d) Transverse Turbulent Intensity Profiles. ut and vt are the rms of the transverse turbulent velocities along the vertical and horizontal diameters, respectively.

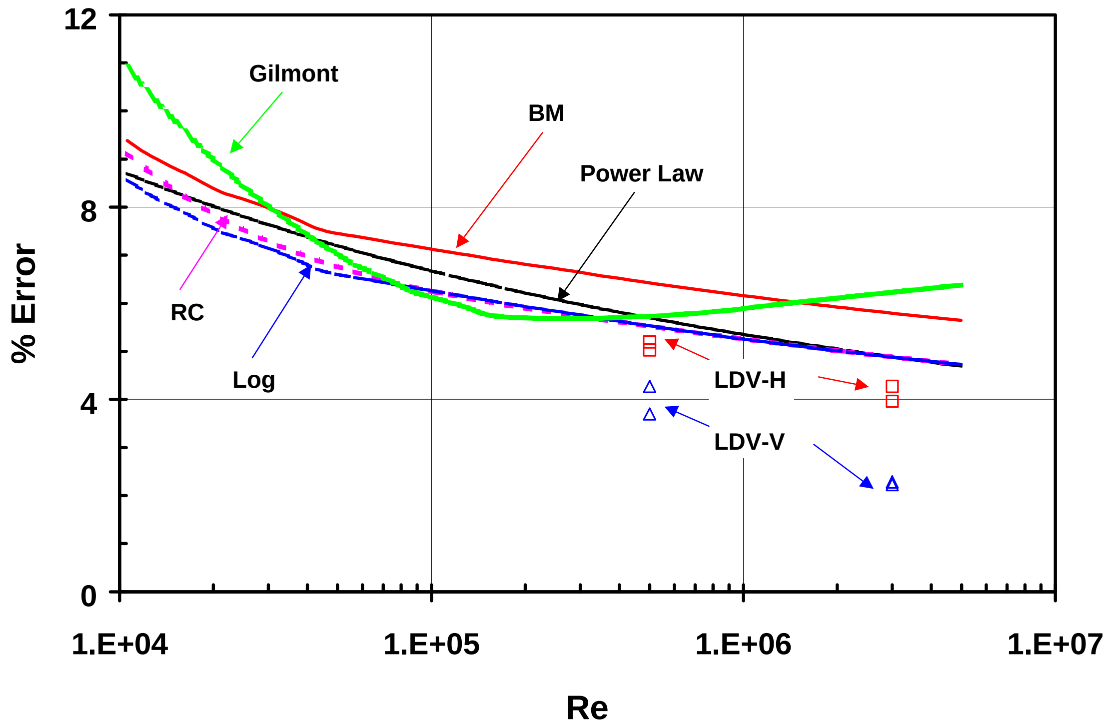

Figure 2. Meter Simulation Errors Resulting from the Assumption of Uniform Flow Profiles for Commonly Used Pipe Flow Distributions. Unnamed profiles are: BM refers to Bogue & Metzner, [6]; LOG refers to logarithmic, [11]; and RC refers to Reichardt, [10]. The designations LDV-H and LDV-V refer, respectively, to the horizontal and vertical profiles plotted in Figure 1(a).

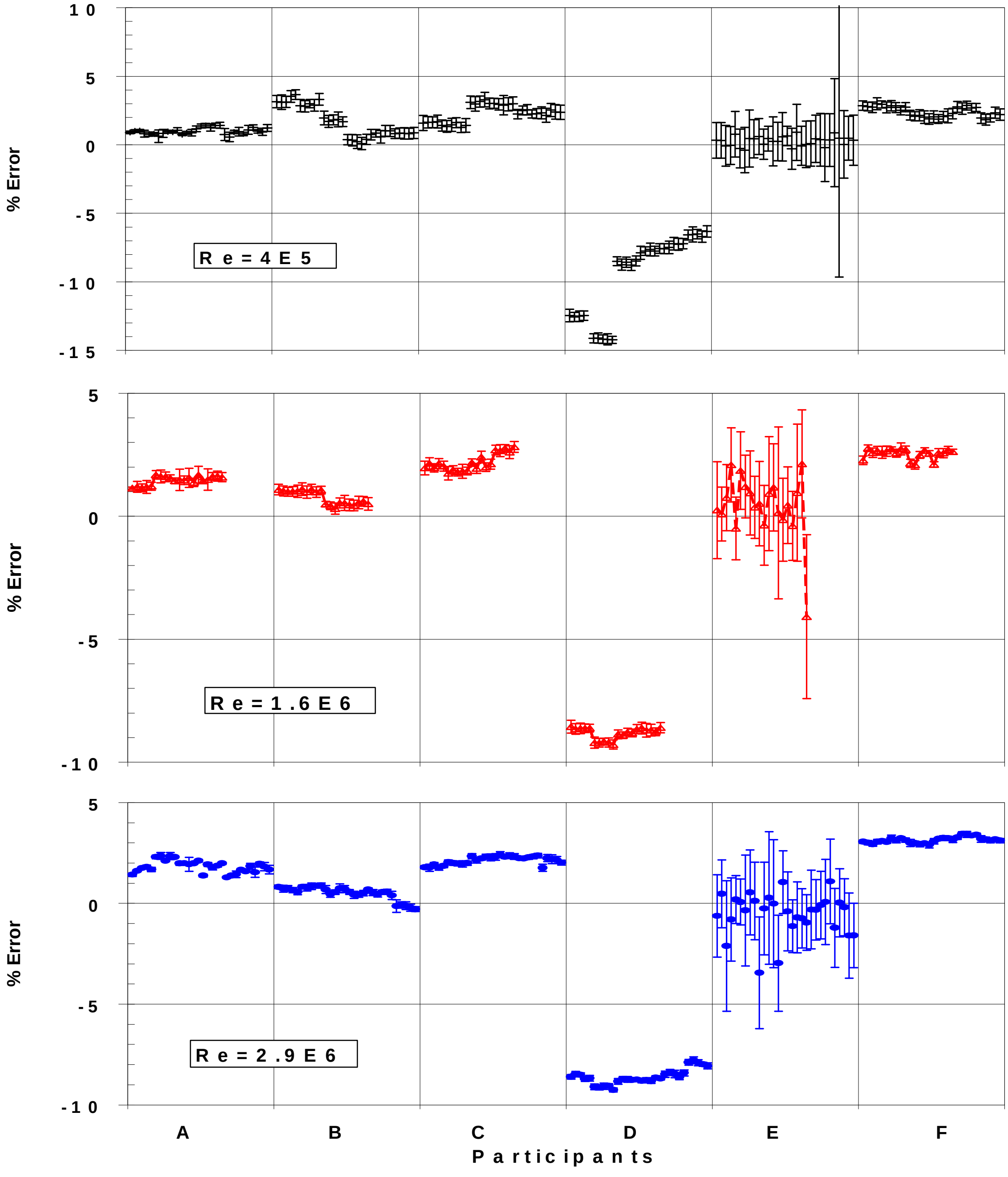

Figure 3. Error Assessment Data for the Participants for Three Flow Rates as a Percentage Difference from the NIST Gravimetric Standards Result. The data, plotted sequentially, left to right, are the results for each timed collection for the six tests, T1-T6. Error bars show one standard deviation of the time varying meter indication about its temporal mean.

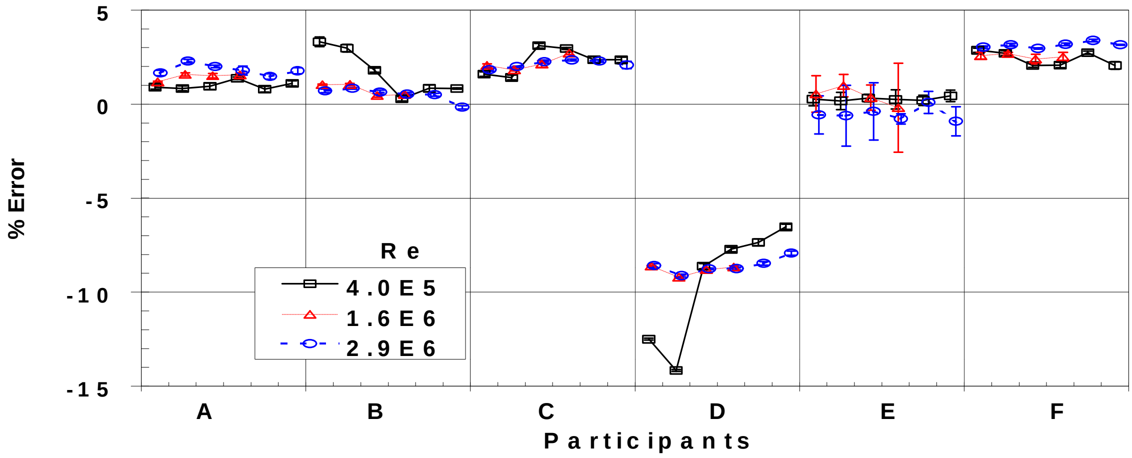

Figure 4. Mean Value and Repeatability Results for Each of the Six Tests for All Flow Rates. Values plotted are averages of the five successive error assessments in each test condition relative to the NIST gravimetric standards; error bars show repeatability as defined as one standard deviation of these 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. It is noted that there is no T5 and T6 data for Re=1.6E6.

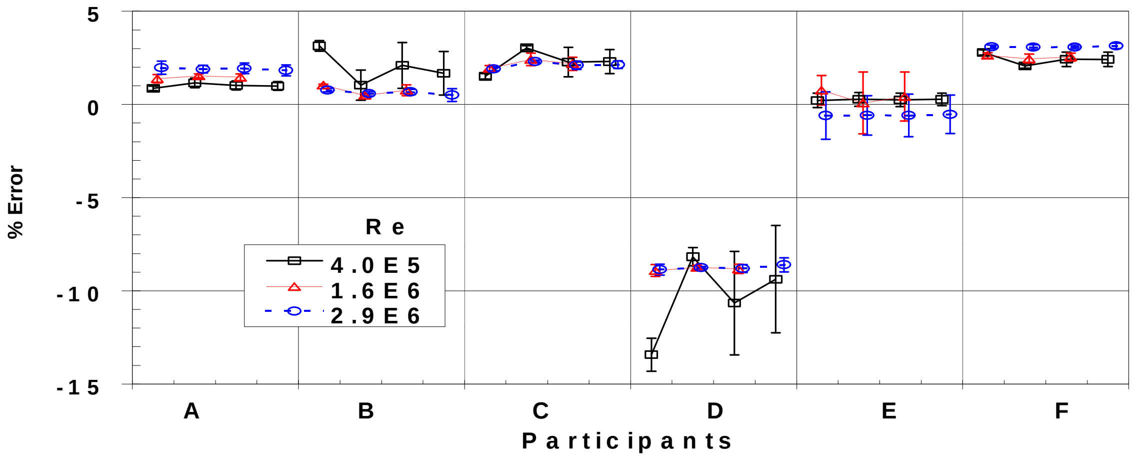

Figure 5. Mean Value and Reproducibility Results for Participants for All Flow Rates. The mean values and reproducibilities are plotted left-to-right for each participant, where: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4; T1-4 are for the 20 values in Tests 1-4; and T1-6 are for 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.

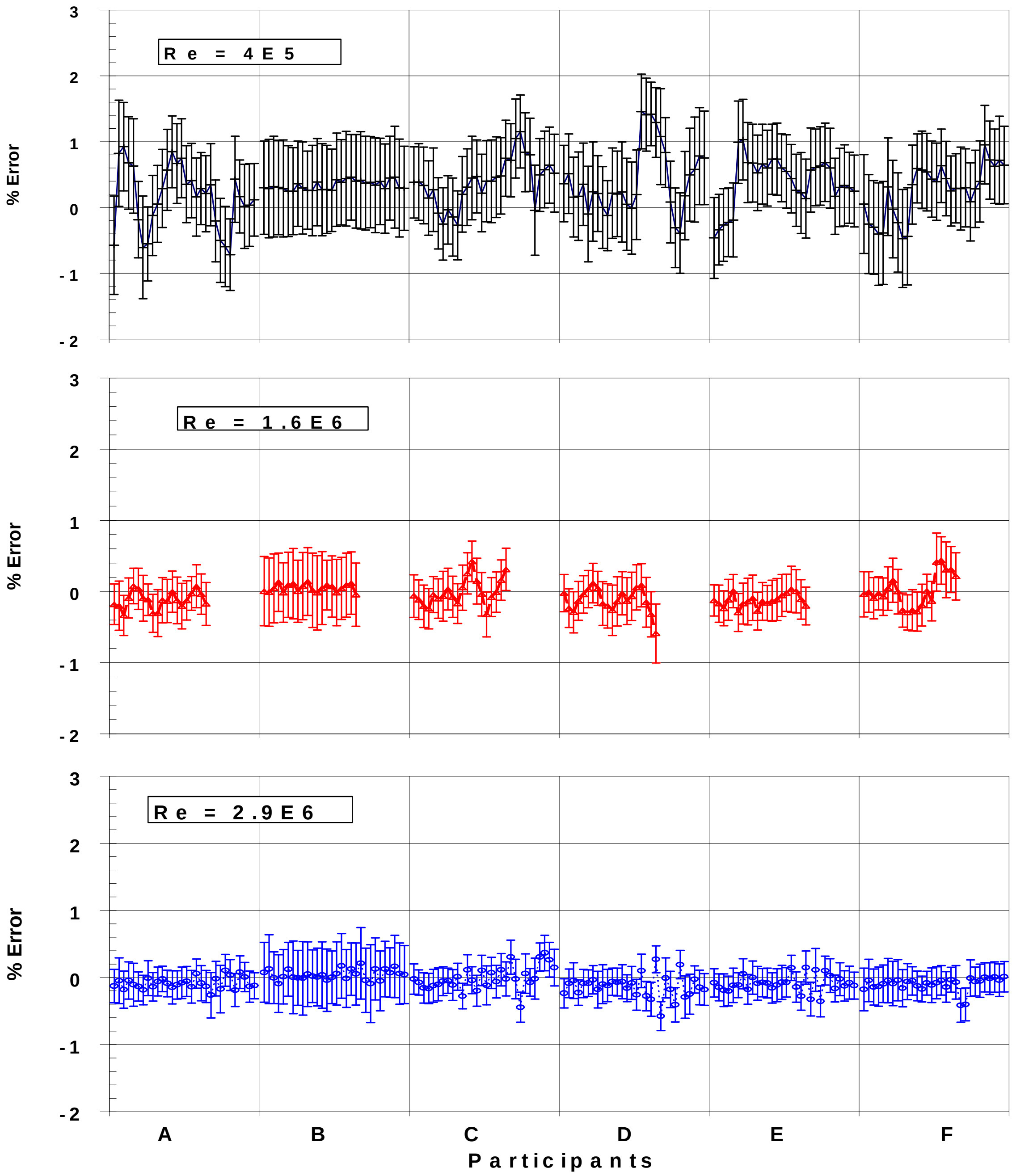

Figure 6. Mean Value Results for the In-Line Ultrasonic Flow Meter through All of the Tests of the Participating Meters Expressed as a Percentage Difference from the NIST Gravimetric Standards Result. It is noted that there is no data for T5 or T6 for Re=1.6E6. Error bars show one standard deviation of the time-varying meter indication about its temporal mean value during each timed-collection.

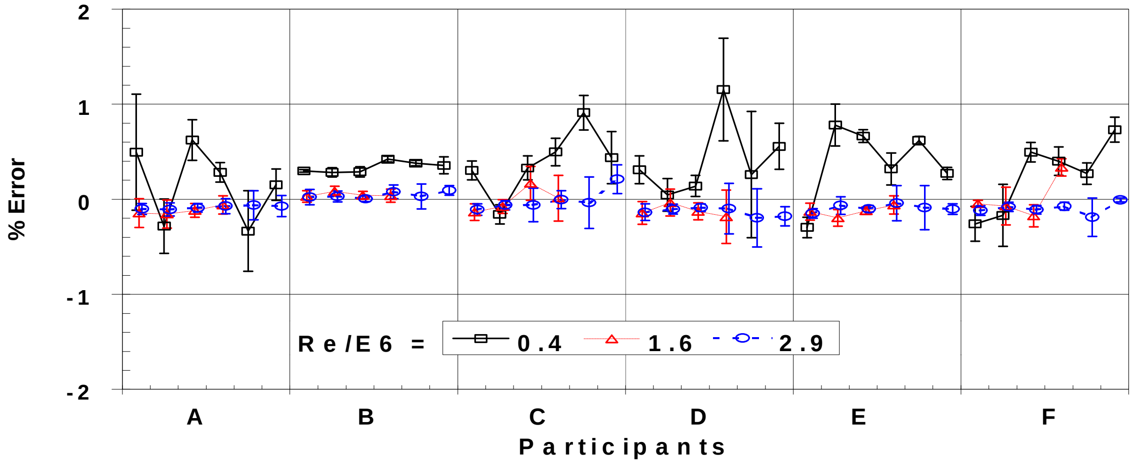

Figure 7. Mean Value and Repeatability Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During the Tests of Each Participant. Error bars show repeatability as defined as one standard deviation of the five successive error assessments relative to the NIST gravimetric standards about their mean value. The six results sequentially plotted, left-to-right, during the tests of each participant for each flow are, respectively, T1 to T6. It is noted that there is no T5 and T6 data for Re=1.6E6.

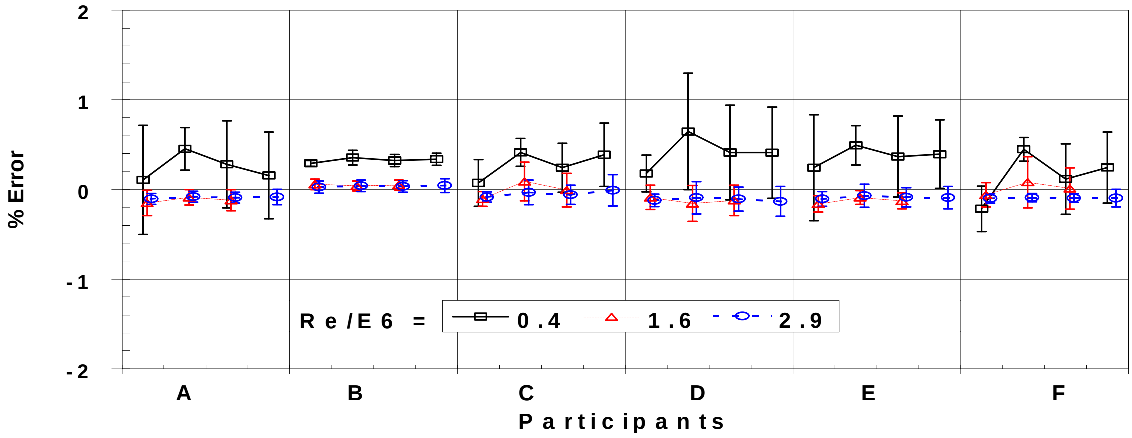

Figure 8. Mean Value and Reproducibility Results for the In-Line Ultrasonic Flow Meter for All Flow Rates During the Tests of Each Participant. The mean values and reproducibilities denoted: T1-2 and T3-4 are for the 10 values in Tests 1-2 and Tests 3-4, respectively; T1-4 are for the 20 values in Tests 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.