Measuring wet-gas flow rate through the V-Cone with neural nets

Haluk Toral and Shiqian Cai
Petroleum Software Ltd.
Richard Steven and Robert Peters
McCrometer

ABSTRACT

The paper presents measurements taken at the National Engineering Laboratory (UK), K-Lab (Norway) and CEESI (USA) wet gas test loops. The test matrices cover a range of conditions up to 15% liquid volume fraction and operating pressure up to 90 bar. Differential and absolute pressure signals were sampled at high frequency across V-cone meters. Turbulence characteristics of the flow captured in the sampled signals were characterized by pattern recognition techniques and related to the fractions and flow rates of individual phases.

1 INTRODUCTION

Wet gas measurements were conducted under a wide range of conditions with a V-cone meter in the test loops at National Engineering Laboratory (UK), K-Lab (Norway) and Colorado Engineering Experiment Station - CEESI (USA). Measurements, comprising high frequency signals from pressure and differential pressure sensors, were analysed by characterisation of the turbulence properties of the flow by means of a pattern recognition / neural net methodology described in previous publications (1,2)

A 6" V-cone meter of 0.75 beta was tested at NEL and K-Lab with test fluids nitrogen/kerosene and natural gas/hydrocarbons respectively. Analysis of the results of these tests carried out by the methodology to be described in further detail in this paper showed that the turbulence characteristics could be classified by a common neural network despite the differences in the fluid properties (1). A schematic of the V-Cone is shown in Figure 1.

In this paper new data is published from tests conducted at CEESI with a 4" diameter V-cone where field gas and decane were used as test fluids. The investigation is advanced further by extending the scope of the common neural net model based on NEL and K-Labs to CEESI test matrix. Thus the objective of the present test was to find out whether a common neural net model can be established for representing flow through different diameter V-cone devices under different operating conditions.

CEESI test matrix comprised gas flow rates at 100, 200, up to 300 m^3/hr at three pressures levels 15, 45 and 75 bar. For each gas and pressure combination, a set of liquid flow rates were passed corresponding to Lockhart-Martinelli parameters from 0, 0.025, 0.05, 0.1, 0.15, 0.2 to 0.25 (GVF from 100% to 93.25%). The test matrix comprised 84 test points.

The V-cone was connected to high frequency absolute and differential pressure gauges and a portable PC as the data acquisition system. The signals were sampled and analysed by PSL's ESMER methodology. The essence of ESMER is to extract characteristic features from fluctuating differential and pressure signals sampled at high frequencies. Examples of such features can be given as standard deviation in the amplitude domain and linear prediction coefficients in the frequency domain. The efficiency of the features for discriminating between different flow conditions is assessed by means of the Saliency test. The features were then related to the superficial velocities of individual phases by means of a back-propagating neural net (1,2). A data flow diagram of the concept is shown in Figure 2.

2 INSTALLATION OF THE METER AT CEESI

CEESI high pressure wet gas facility is a recirculation loop around a two phase separator. The test section has 4" schedule 80 pipe. The fluids used are natural gas and decane. The facility operates at a temperature of approximately 30 °C at a maximum pressure of 90 bar. The single phase volumetric gas flow rates can be varied from approximately 0 to 27 m/s. Fluid densities used in the present tests are summarized in Table 1.

Table 1. Test Fluid Properties

Pressure bar Temperature=30°C	Number Measurements	Density of Natural Gas, kg/m3	Density of Condensate, kg/m3
15	21	11.49	731.82
45	43	38.14	718.21
75	20	65.65	707.71

Flow rates are measured on each single phase stream prior to liquid injection into the gas stream. Flow measurements, as well as pressure and temperature measurements at several points of the loop, are automatically transmitted to a data acquisition system and processed by a computer. The reference gas flow rate is measured by a turbine meter with a Venturi meter back up. The liquid reference flow rates were measured by two calibrated Coriolis meters in series sized to cover the full liquid injection range.

Test matrix points from NEL, K-lab and CEESI are shown in Figure 3. The matrices were selected to test the performance of the ESMER V-cone meter against gas and liquid loading variations similar to those under wet gas field conditions.

ESMER requires approximately 60 seconds to record the AP (absolute pressure) and DP (differential pressure) signals at each matrix point. This consists of a 40 seconds sampling period followed by a period during which the signals are processed. The AP and DP signals are sampled at the 800 Hz.

In the present tests, signals were sampled for a total of around 4-5 minutes at each matrix point. During this period ESMER collected between 4-5 repeat samples (of 40 seconds duration). Typically the time between each matrix point was 5 to 10 minutes when changing the gas and/or liquid flow rate/s (to allow for changing and stabilisation of the conditions). A longer stabilisation period was necessary when changing the liquid flow rates.

3 OVERREADING

The consistency of the data was first assessed by plotting the over-reading factor against Lockhart Martinelli parameter in both cases (3). The calculation of the V-Cone meter wet gas over-reading is based on the following equation:

Over-reading (OR) = $\sqrt{\frac{\Delta p_{tp}}{\Delta p_g}}$

where the following term is calculated from V-Cone constants and dry gas mass flow rate reference measurement as follows:

$$\sqrt{\Delta p_g} = \frac{\dot{m}_{g,ref}}{EC_d A_d \sqrt{2\rho_g}}$$

E is velocity of approach factor = $(1/\sqrt{1-\beta^4})$=1.2095

C_d is the discharge coefficient of the V-Cone meter with dry gas flow (which is a function of the Reynolds number for maximum accuracy, but approximated here to a constant value) = 0.778

A_d is the minimum cross section area through the meter= $(\frac{\pi\beta^2 D^2}{4})$ = 0.4295

$\dot{m}_{g,ref}$ is the dry gas mass flow rate by the reference

and

Δp_{tp} is the mean two phase differential pressure as measured by the DP sensor.

The over-reading at three pressure levels of 15, 45 and 75 bar is shown in Figure 4. The mean differential pressure used in this graph was obtained by averaging the ESMER DP signal over the normal sampling period. The same graph was also plotted with the differential pressure measurement made by the standard sensors, as shown in Figure 5 The difference between the two sets of graphs are shown in the table below in the term of the difference in the RMS of the two data sets given by:

RMS variation between the two data sets = $\sqrt{1/N \sum_N (\frac{OR_{ESMER} - OR_{Standard}}{OR_{Standard}} X 100\%)^2}$.

Where OR_{ESMER} is over-reading recorded by the ESMER fast DP sensor; $OR_{Standard}$ is over-reading recorded by the standard DP sensor sampling at 5Hz and N is the total number of test points in CEESI test.

Table 2. Comparison of over-reading based on standard sensor vs fast sensor

Pressure	Number of Measurement	RMS (%)
15	**21**	**1.58**
45	**43**	**1.61**
75	**20**	**1.23**

The difference between the average measurement made by the fast sensors and the standard sensors was considered to be within the range of expected accuracy. Therefore a fast DP sensor can be used in a wet gas meter in place of a standard (damped) DP sensor satisfying the requirements of ESMER and a conventional correlation based method at the same time.

4 TEST RESULTS

The analysis is presented in four sections named as: repeatability test (CEESI), independent test (CEESI), general modelling (K-Labs, NEL and CEESI together) and cross test (K-Labs against NEL)

4.1 Repeatability test CEESI

The neural net models were trained on every available matrix point at 15 bar (21 points), 45 bar (43 points) and 75 bar (20 point) of the CEESI data set. As 4 to 5 sample records were collected at each matrix point, one of these was not used in the training process and saved for the repeatability (back) test of the neural net. The results of the repeatability test are shown in Table 3.

Table 3. Repeatability test

CEESI Data	RMS (%)		
Pressure 15 – 75 bar	**Full range**	**Low Liquid X<0.1**	**High Liquid X>=0.1**
Gas	1.01	0.88	1.16
Liquid	13.68	15.50	10.79
Number of Test Points	**84**	**48**	**36**

4.2 Independent test CEESI

In the independent test the neural net is tested with a set of matrix points not included for training. Thus, for testing, 12 points were selected at X = 0.025 representing typical low liquid conditions and 12 points at X=0.15 representing medium liquid loading conditions at 15,45, 75 bar. These points were not used in training the neural net. Test results are shown graphically on Figures 6-9 and summarised in Table 4.

Table 4. Independent test

CEESI Data	RMS (%)		
Pressure 15 – 75 bar	**Full range**	**Low Liquid X<0.1**	**High Liquid X>=0.1**
Gas	1.13	1.13	1.13
Liquid	26.06	28.30	23.61
Number of Test Points	24	12	12

4.3 General model - K-lab, NEL and CEESI

NEL, K-lab and CEESI data sets were combined in a common training and testing study. The distribution of training and testing points is shown in Table 5.

Table 5. Distribution of training and testing points

Laboratory	Pressure bar	Number of Training Points	Number of Testing Points
K-lab	55	41	20
K-lab	90	49	15
NEL	60	12	11
CEESI	45	31	12
CEESI	75	14	6

General model test results are shown in detail in Figures 10-13 and summarised in Table 6. The gas rate prediction was under RMS 4% under all liquid conditions. There were a total of 5 measurements (out of 64 test points) outside the 5% error band for gas measurement and the maximum error encountered at the highest and lowest extremities were +11% and -6%..

The prediction of the liquid rate varied from an RMS of 61.37% at low liquid loading (X<0.1) to RMS of 20.28 at high liquid loading (X>0.1).

Table 6. General model - independent test

	RMS (%)		
Pressure 45 - 90 bar	**Full range**	**Low Liquid X<0.1**	**High Liquid X>=0.1**
Gas	3.27	2.53	3.74
Liquid	43.35	61.37	20.28
Number of Test Points	64	28	36

4.4 Cross test between K-lab and NEL

The objective of this study was to see the portability of neural model by training on the measurements taken from one laboratory alone and testing on another. We carried out a series of tests whereby the original neural net trained on 90 points from K-labs was tuned up with 0,1,2,3,4,5,6 points taken from NEL and tested against remaining NEL points. We have not reported the result of 0 tune up because the results were not worth reporting. However, an encouraging trend appeared when the parent neural net (K-labs) was trained with 2,4,5,6 points from the target (NEL) and tested against the remaining points (ie tested with 21,19,18,17 points). The results are tabulated in Tables 7 – 10 and the trend is shown graphically in Figure 14.

Table 7. General model - cross test (re-trained with 2 NEL points)

K-lab vs NEL	RMS (%)		
Pressure 45 - 90 bar	Full range	Low Liquid X<0.1	High Liquid X>=0.1
Gas	17.25	12.31	20.19
Liquid	82.23	88.08	77.55
Number of Test Points	21	9	12

Table 8. General model - cross test (re-trained with 4 NEL points)

K-lab vs NEL	RMS (%)		
Pressure 45 - 90 bar	Full range	Low Liquid X<0.1	High Liquid X>=0.1
Gas	17.01	19.43	14.51
Liquid	67.43	94.63	24.11
Number of Test Points	19	8	11

Table 9. General model - cross test (re-trained with 5 NEL points)

K-lab vs NEL	RMS (%)		
Pressure 45 - 90 bar	Full range	Low Liquid X<0.1	High Liquid X>=0.1
Gas	3.64	3.12	4.02
Liquid	40.94	43.97	38.35
Number of Test Points	18	8	10

Table 10. General model - cross test (re-trained with 6 NEL points)

K-lab vs NEL	RMS (%)		
Pressure 45 - 90 bar	Full range	Low Liquid X<0.1	High Liquid X>=0.1
Gas	3.8	3.07	4.35
Liquid	31.40	36.46	26.08
Number of Test Points	17	8	9

Finally in Figures 15 – 17 we show the detailed distribution of predictions versus actual measurements for Table 10 (ie after in-situ training with 6 NEL points)

5 CONCLUSIONS

Turbulence characteristics across V-cones measured in three wet gas tests flow loops with different fluids, operating conditions and diameters were modelled by a common neural net model. The RMS accuracy of predictions were under 4% for the gas phase. Maximum error in gas rate measurement was +11% and -6%, The RMS accuracy of the liquid prediction deteriorated from 20% at high liquid loading to 61% at low liquid loading.

In the cross test (training on one laboratory and testing on another), comparable levels of accuracy can be obtained after some in-situ training of the neural net.

6 REFERENCES

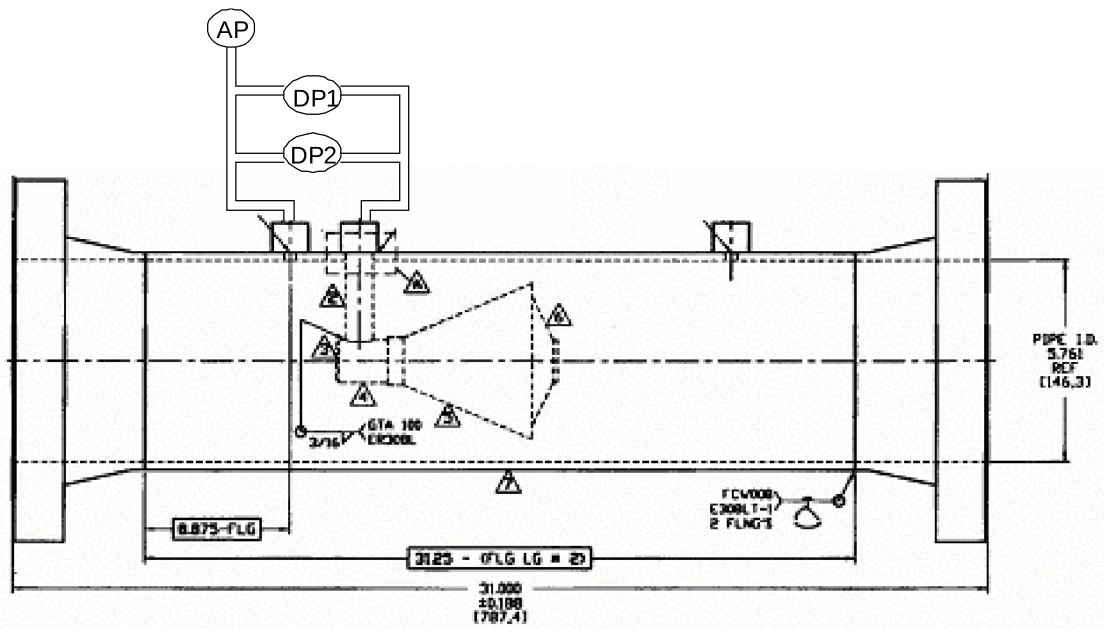
[1] Characterization of the turbulence properties of wet gas flow in a V-Cone meter with neural nets 22nd North Sea Flow Measurement Workshop October 2004 St Andrews Haluk Toral, Shiqian Cai, Petroleum Software Ltd Richard Steven, Robert Peters, McCrometer

[2] Experience in field tuning and operation of a multiphase meter based on neural net characterization of flow conditions Shiqian Cai and Haluk Toral (Petroleum Software Limited), Dasline Sinta, Meramat Tajak, (Sarawak Shell Bhd Malaysia) FLOMEKO 2004 Beijing 14-17 Sept. 2004

[3] David Stewart, David Hodges, Richard Steven, R J W Peters Wet gas metering with V-cCone meters.20th North Sea Flow Measurement Workshop 22-25 October 2002, Perthshire, Scotland.

ACKNOWLEDGEMENT

Our thanks are due to CEESI, McCrometer for facilitating these tests and in particular to Bob Peters and Richard Steven of McCrometer and Charlie Britton, Josh Kinney of CEESI for their support during the tests.



DP1: Standard DP
DP2: ESMER Fast DP
AP: ESMER Fast AP

Figure 1. Schematic Diagram of V-Cone

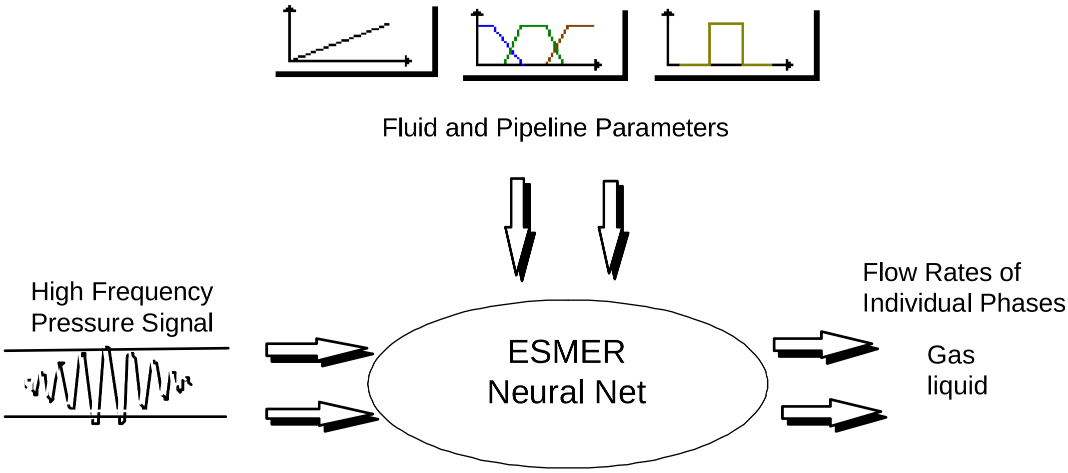


Figure 2. Schematic diagram of the ESMER concept

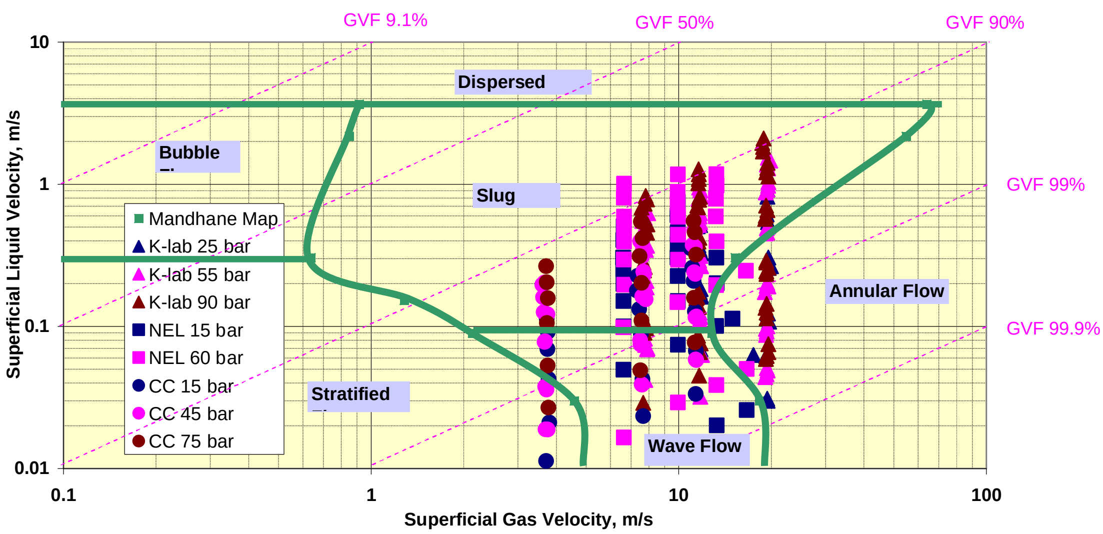


Figure 3. Operating envelope of NEL, K-lab and CEESI test data

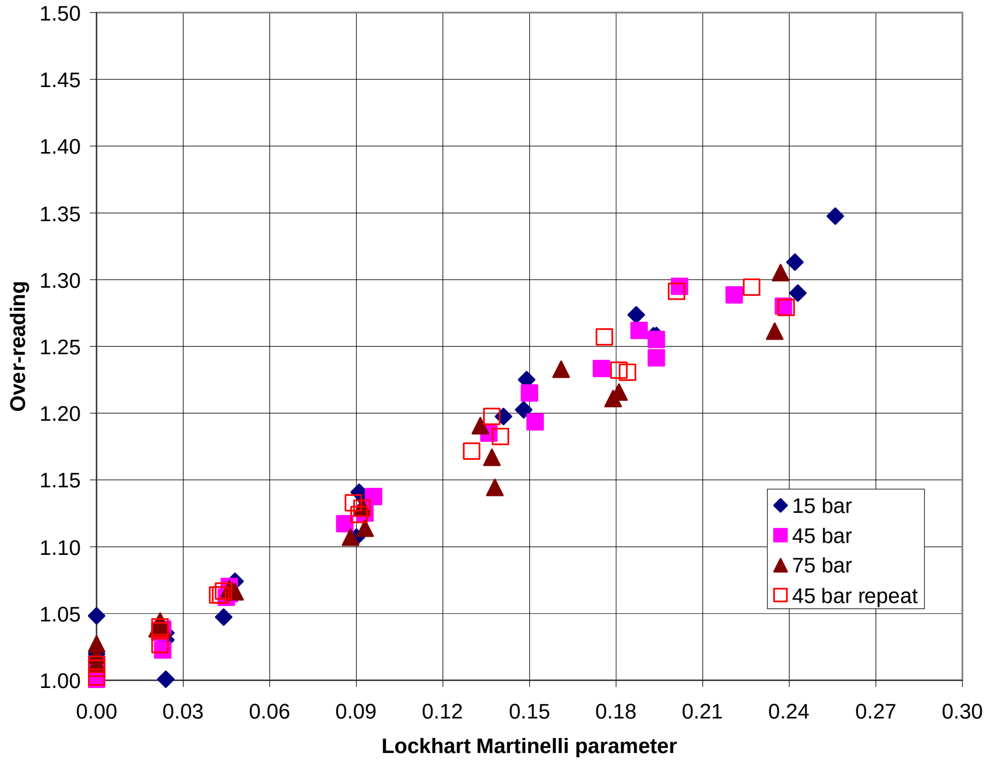


Figure 4. Over - reading of fast DP

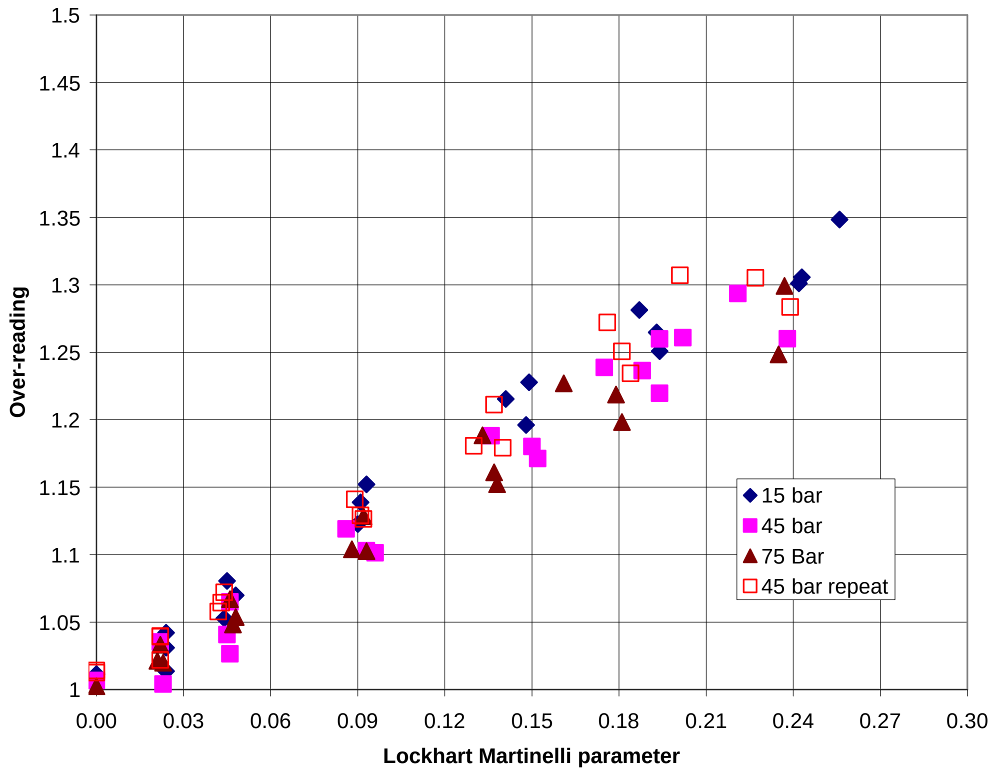


Figure 5. Over-reading of standard DP

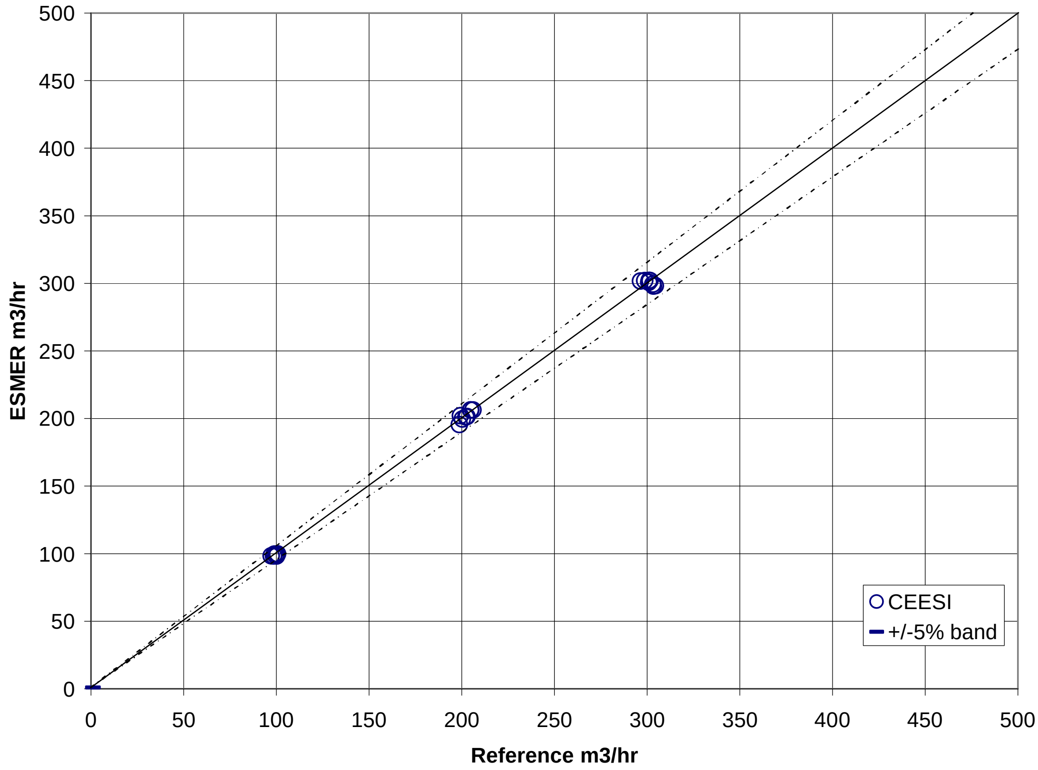


Figure 6. Meter gas flowrate vs. reference gas flowrate (independent test)

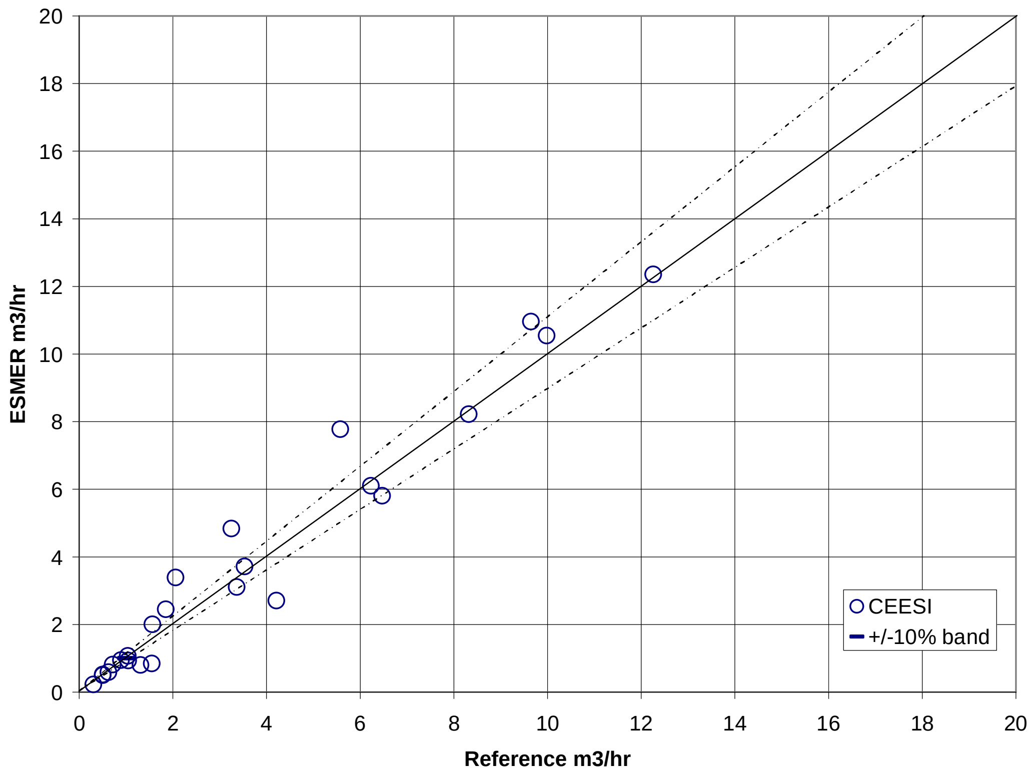


Figure 7. Meter liquid flowrate vs. reference liquid flowrate (independent test)

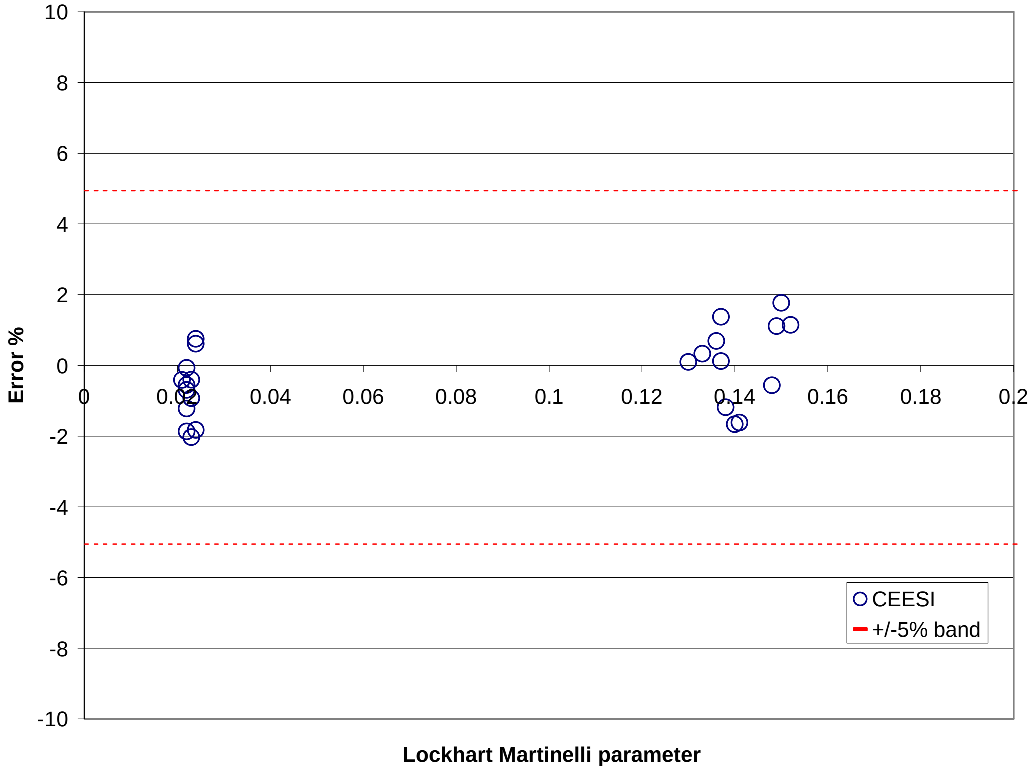


Figure 8. Meter gas flow rate error vs Lockhart Martinelli (independent test)

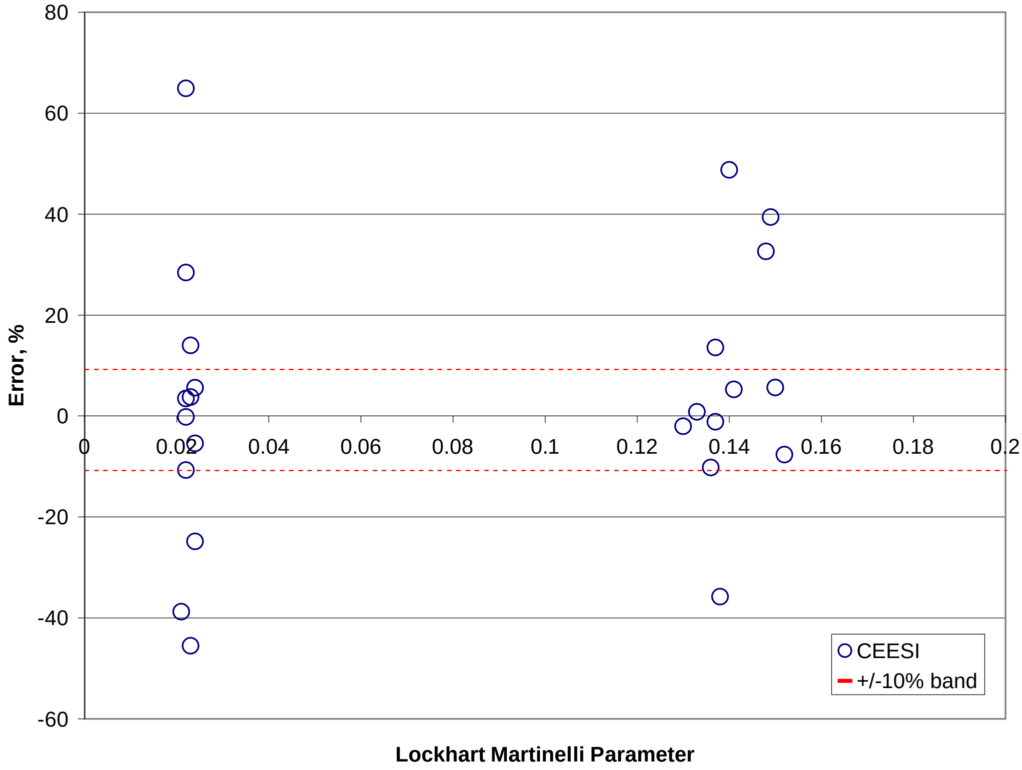


Figure 9. Liquid flowrate error vs Lockhart-Martinelli (independent test)

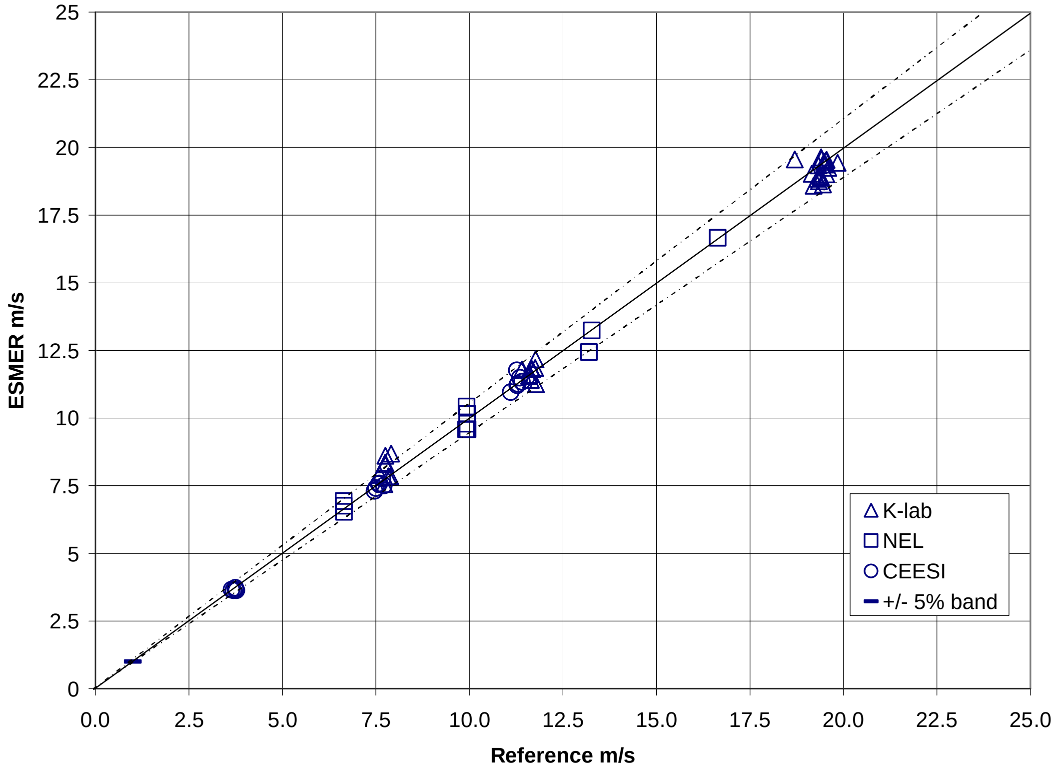


Figure 10. Meter gas flowrate vs. reference gas flowrate (general modelling)

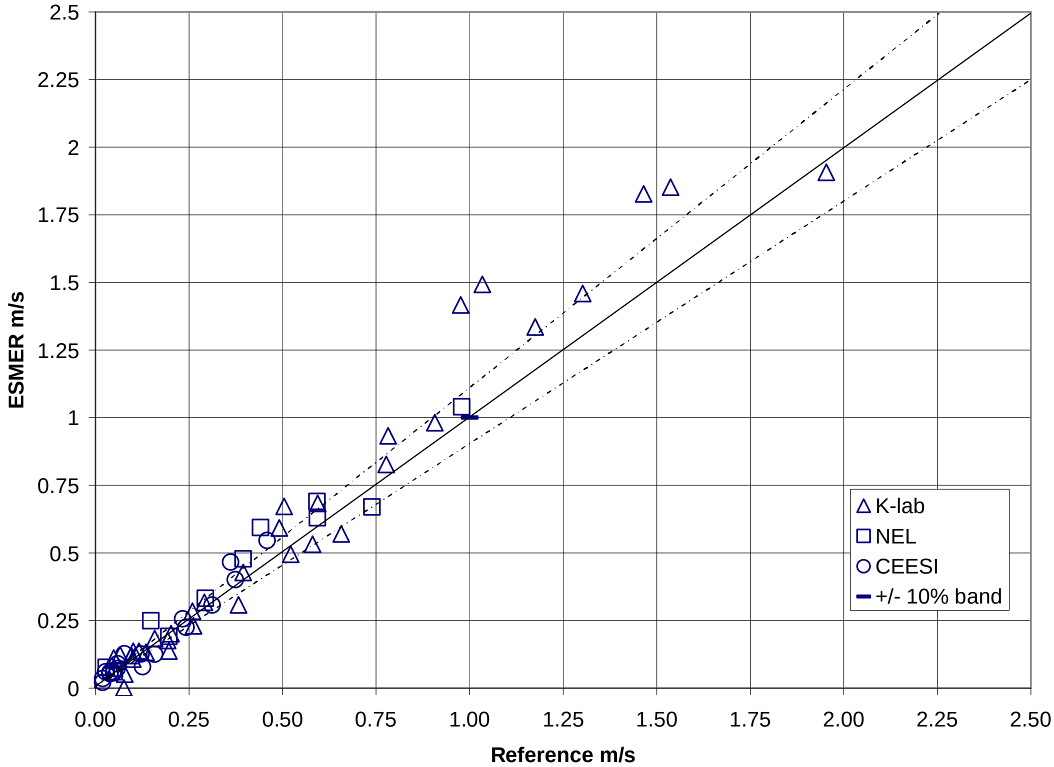


Figure 11. Meter liquid flowrate vs. reference liquid flowrate (general modelling)

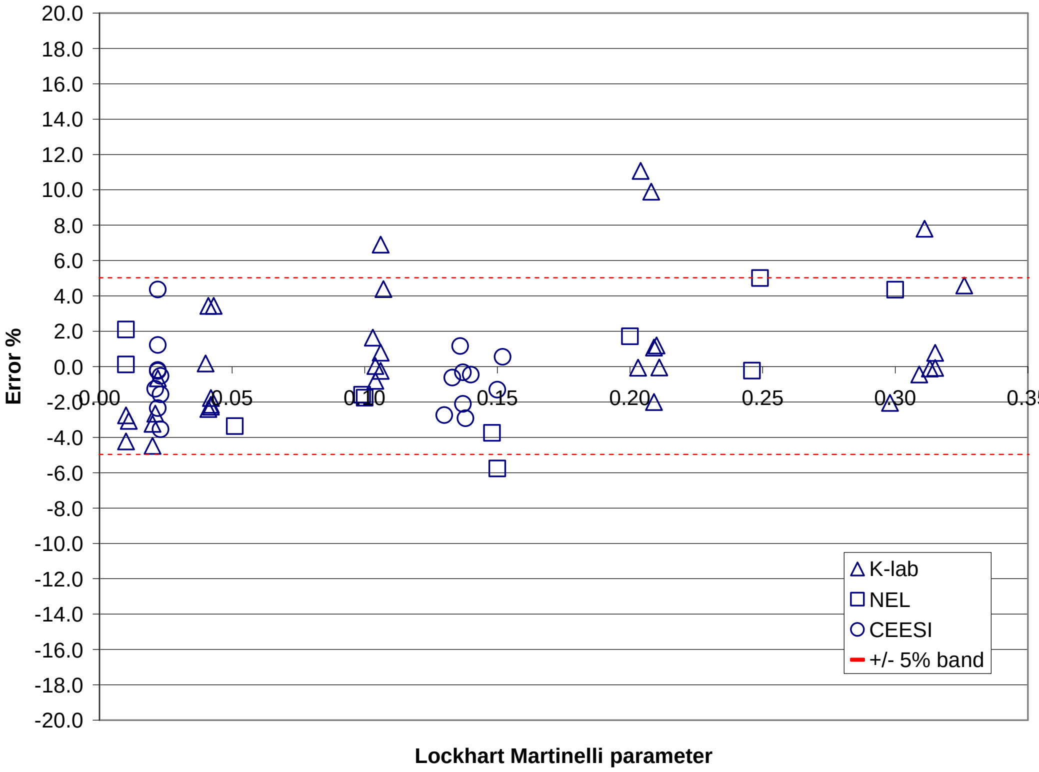


Figure 12. Gas flowrate error vs. Lockhart-Martinelli parameter (general modelling)

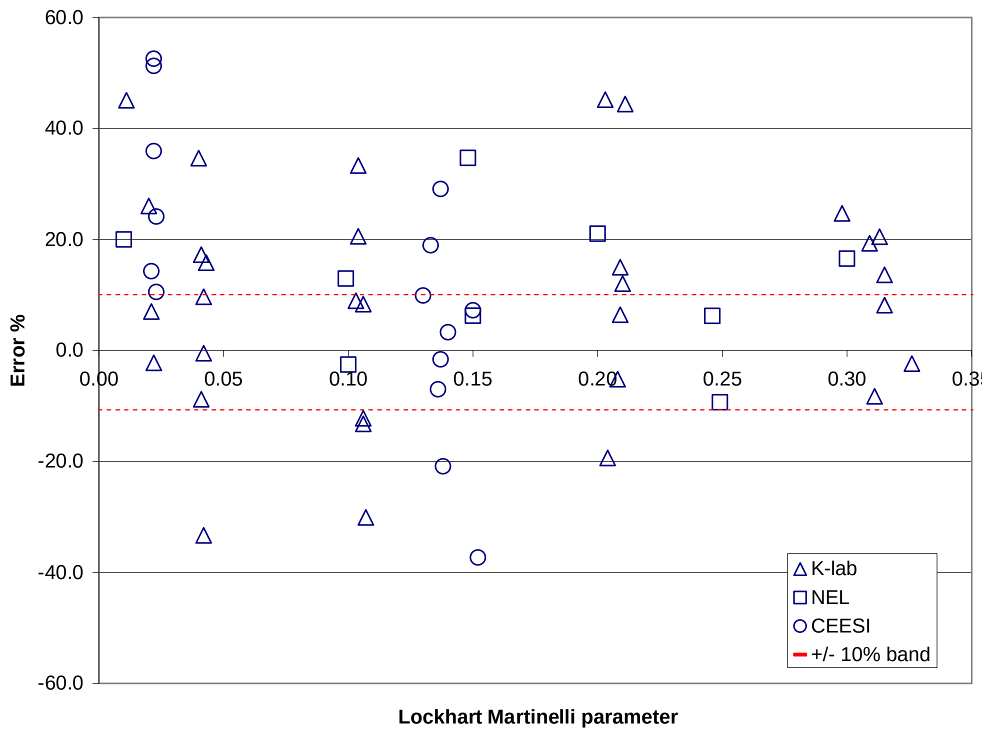


Figure 13. Liquid flowrate error vs. Lockhart-Martinelli parameter (general modelling)

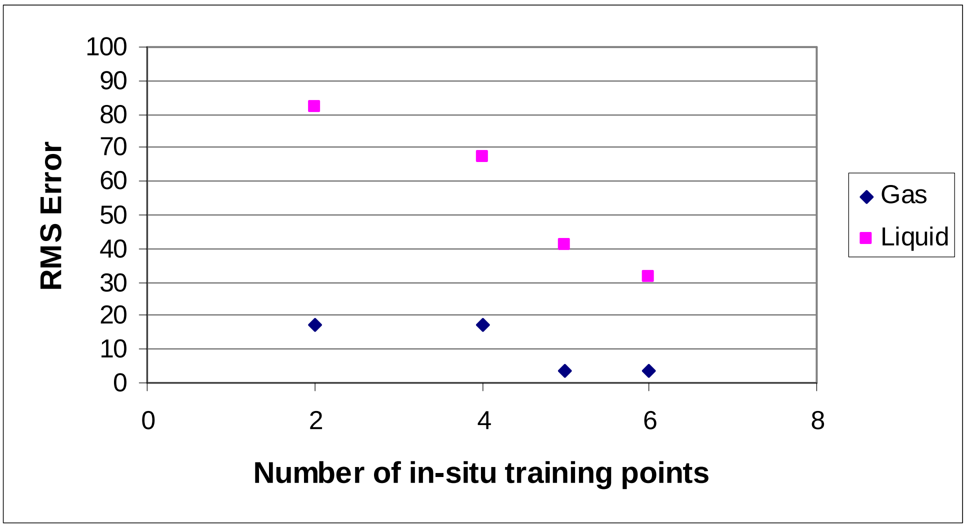


Figure 14. Reduction of error with in-situ training points (cross test)

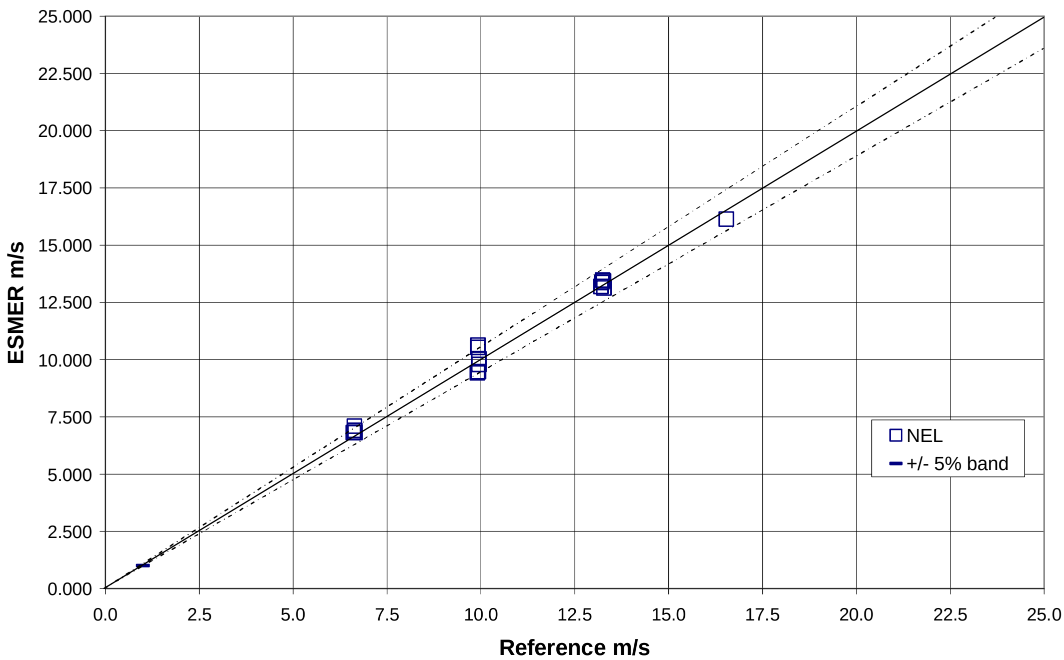


Figure 15. Meter gas flow rate error vs Lockhart Martinelli (cross test)

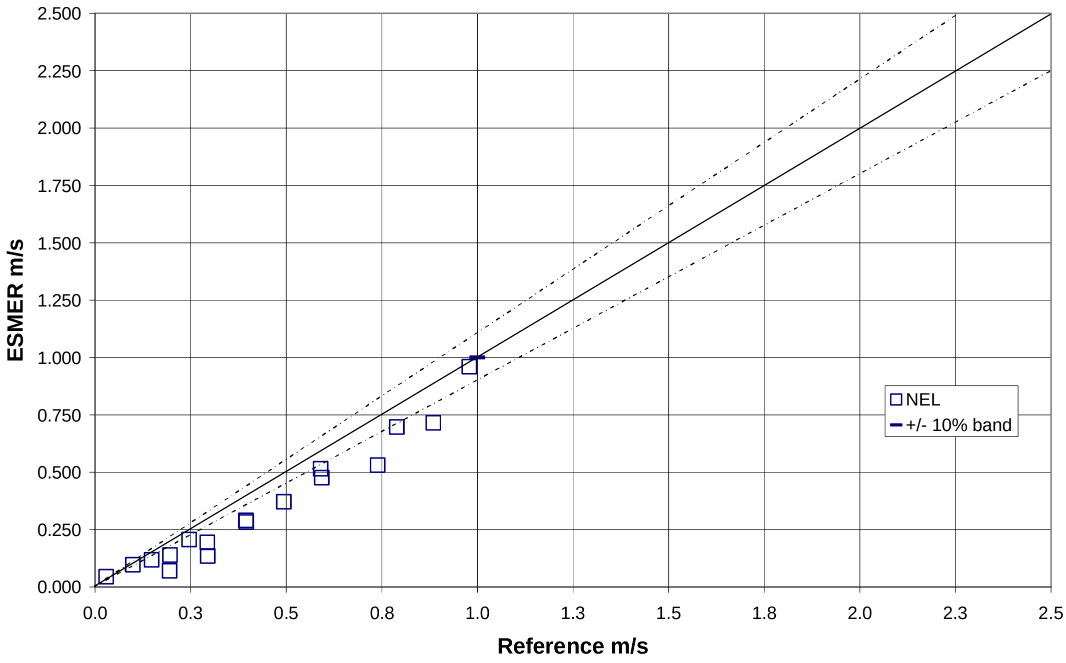


Figure 16. Meter liquid flowrate vs. reference liquid flowrate (cross test)

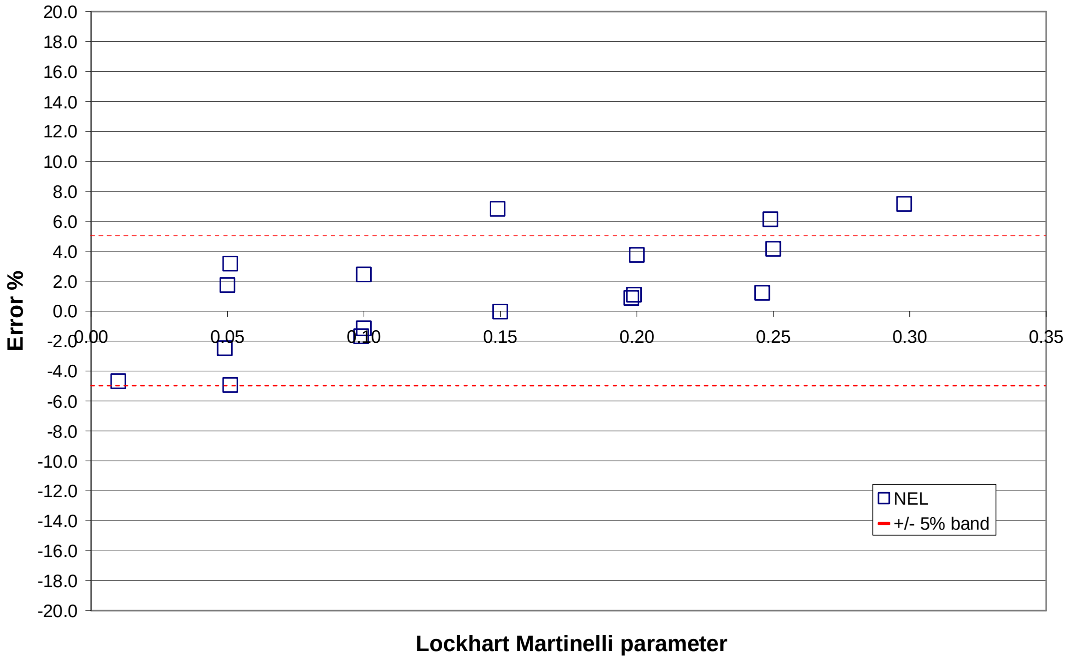


Figure 17. Gas flowrate error vs. Lockhart-Martinelli parameter (cross test)

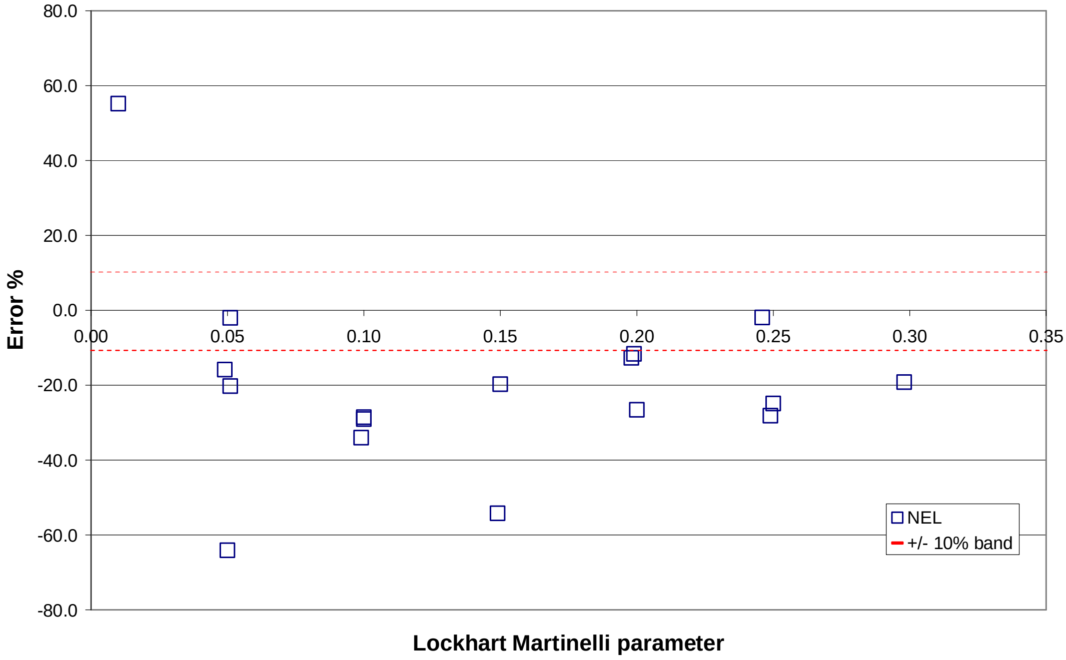


Figure 18. Liquid flowrate error vs. Lockhart-Martinelli parameter (cross test)