I CIMMEC
1ST INTERNATIONAL CONGRESS ON MECHANICAL METROLOGY
October, 08 – 10, 2008, Rio de Janeiro, Brazil

THE DESIGN AND IMPLEMENTATION OF A FULLY AUTOMATED CROSSFLOAT SYSTEM FOR THE COMPARISON OF PISTON GAUGES IN BOTH GAUGE AND ABSOLUTE MEASUREMENT MODES

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Abstract: The pressure crossfloat is the most common method for determining the area of a piston-cylinder, normally in a gauge mode and manual operation. A fully automated crossfloat system, can perform unattended crossfloats to determine the effective area in either absolute or gauge mode. This paper describes the design, challenges and results of crossfloats tests performed over six months using the full automated system.

Keywords: Pressure, effective area, crossfloat, automation, Base Ratio, Direct Ratio.

1. INTRODUCTION

Crossfloating is a method for comparing two piston gauges with two possible common goals. One is to simply compare the pressure output defined by two piston gauges. The other is a method of determining the effective area of the piston-cylinder used in a piston gauge. In either case the method is widely used and well documented, but has historically been a manual operation that is difficult and time consuming. Though a crossfloat is as common as there are piston gauges, few pressure measurement laboratories are consistently successful in producing results within required uncertainty limits.

DHI manufactures piston gauges that have a very high level of precision. The typical pressure measurement uncertainties offered with the piston gauges do not allow for very much added uncertainty from crossfloat tests. Historically the workload to deliver these systems is excessive due to the low target uncertainties required for effective area and the time consuming process of establishing an equilibrium in a manual crossfloat. With an increasing demand on production levels for piston gauges, performing crossfloats manually is a burden on laboratory personnel and equipment and limits consistent production.

A project was implemented by DHI in early 2006 to design an automated crossfloat system targeted at the most frequently delivered piston gauge systems. The goals of the crossfloat system were to:

- Determine the effective area and performance of DHI gas operated, gas lubricated piston-cylinders.
- Significantly increase production.
- Perform at levels that support target uncertainties for effective area.
- Perform the crossfloat in absolute mode.
- If possible, test the "performance" of a piston-cylinder.

The crossfloating system was successfully implemented and has been used since November 2006 to determine effective area for DHI customer's piston gauges. To date, over 70 piston-cylinder effective area determinations have been performed by the automated crossfloat system.

2. CROSSFLOATING METHODS

When performing a crossfloat, the result of each point taken is defined as an equilibrium. An equilibrium is where two piston gauges are considered to be measuring an equal pressure within the uncertainties defined for that point. In its most fundamental form the equation for an equilibrium state is: (Note: list of variables may be found at the end of this paper)

$$\frac{m_{test} \cdot g_l}{A_{e\,test}} = \frac{m_{ref} \cdot g_l}{A_{e\,ref}} \tag{1}$$

and can be rearranged to determine the effective area of the test:

$$A_{e\,test} = \frac{m_{test} \cdot g_l}{m_{ref} \cdot g_l} \cdot A_{e\,ref} \tag{2}$$

Noting that local gravity drops out of equation 2, the effective area of the test becomes a ratio of the mass loaded on that point when the two piston gauges are in equilibrium. If all the corrections are included then equation 2 becomes [3]:

$$A_{etest}(T_{norm}, P_{test}) \cdot (1 - \lambda_{test} P_{test}) = A_{eref}(T_{norm}, P_0) \cdot (1 + \lambda_{ref} P_{ref})[R_m][R_T] \quad (3)$$

where:

$$R_m = \left[\frac{\sum_I m_{test} \cdot [1 - (\rho_{air}/\rho_{mtest})] + \left(\frac{\gamma \cdot C_{Test}}{g} \right) + \varepsilon}{\sum_I m_{ref} \cdot [1 - (\rho_{air}/\rho_{mref})] + \left(\frac{\gamma \cdot C_{ref}}{g} \right) - A_{eref}(T_{ref}, P_{ref}) \cdot h \cdot (\rho_f - \rho_{air})} \right] \quad (4)$$

and

$$R_T = \left[\frac{1 + (\alpha_{c\,ref} + \alpha_{p\,ref}) \cdot (T_{ref} - T_{norm})}{1 + (\alpha_{c\,test} + \alpha_{p\,test}) \cdot (T_{test} - T_{norm})} \right] \quad (5)$$

Equations 3 through 5 are specifically for gauge mode operation where changes in atmospheric conditions will affect the results of the crossfloat and must be accounted for. It should also be noted that the terms for surface tension may be considered insignificant for gas lubricated piston-cylinders. In absolute mode, because there is not an influence from air buoyancy, and removing the surface tension corrections, equations 3 and 5 remain the same and equation 4 simplifies to:

$$R_m = \left[\frac{\sum_I m_{test} + \varepsilon}{\sum_I m_{ref} - [A_{e\,ref}(T_{ref}, P_{ref\ g}) \cdot h \cdot \rho_f]} \right] \quad (6)$$

If the piston gauges reference levels are at the same height, then only the mass of the reference needs to be included in the denominator of equation 6. Equations 3, 5 and 6 define the Direct Ratio method because the primary measurement of the test's effective area is the ratio of the total mass on each piston gauge corrected by a ratio of the difference in the influence of the thermal expansion correction of the piston-cylinders.

Another method that has been used by DHI for over 25 years, is a variation of the Direct Ratio method. The only difference is that the mass ratios are corrected back to the first point taken in the test, called the base, hence the name Base Ratio was given. The only physical requirement is that the base mass is loaded on the base for all the points in the crossfloat. Because the mass ratio is corrected to the base point the equations for the Base Ratio take on a different form. The reason corrections are made to the base point is to eliminate systematic error and type b uncertainty of the piston and weight carrier mass. The series of equations for the Base Ratio are not given in this paper but can be found in the reference, "The Purpose and Implementation Of A Multi-Piston Cylinder Pressure Calibration Chain" [1]. The automated crossfloat system supports both the Direct Ratio and Base Ratio methods.

3. SYSTEM DESIGN

In addition to full automation, the goals of the design of the automated crossfloat system included the ability to operate in absolute mode. This decision was made not only to eliminate the quantified influences described in the previous section, but also to eliminate un-quantified influences from air drafts. Figure 1 is a schematic of the system and lists the main components used in the automated crossfloat system.

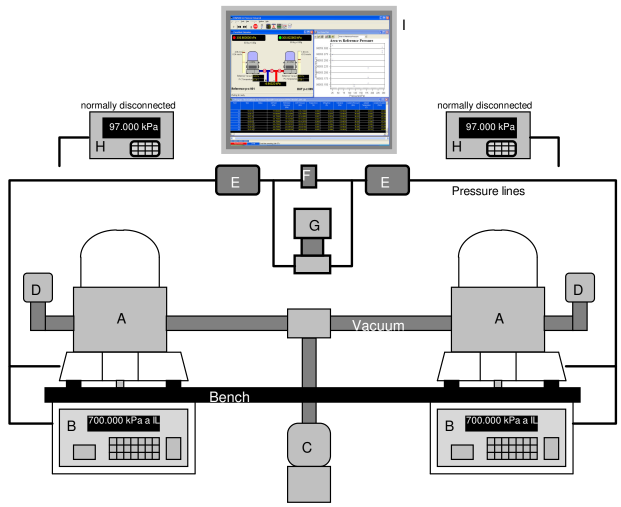

Figure 1. Drawing of the automated crossfloat system.

A. PG7601
   Piston Gauge Platforms with 38 kg automated mass handlers Standard product PG7601 absolute piston gauges to operate the piston-cylinders. Included with these are AMH-38, 38 kg mass sets with a resolution of 100 grams allows automated mass handling for the crossfloats while in absolute mode without breaking vacuum.
B. PPC3-A7M Pressure controllers
   7 MPa pressure controllers used to float and maintain float as the crossfloat points are taken. These controllers work in static mode and isolate themselves from the measurement circuit while data is taken.
C. Turbo and roughing pump
   Since the vacuum is not broken while changing masses the pressure around the bell jar is maintained below 1 Pa with the use of a turbo-molecular vacuum pump.
D. Vacuum gauge
   Measures the residual pressure underneath the bell jar for each PG7601. This value is converted to mass and added to the mass terms for both the direct and base ratio methods.
E. Constant volume valves
   Used to isolate the piston gauges so that when required the pressure controllers can individually re-float the pistons. Opening and closing these valves will not significantly effect the float position generated by the controllers.
F. Isolation valve (for zeroing)
   Used to open the high pressure port of the transmitter to the low side to allow for zeroing of the transmitter at each line pressure.
G. Differential pressure transmitter
   High End industrial pressure transmitter used to measure the difference in pressure between the two piston gauges. Used are

±1 and ±5 kPa differential ranges. Pressure readings are converted to mass values for the term ε in the direct and base ratio methods.

H. RPM4 Pressure monitors
Used when necessary to measure deviations in pressure from changes in piston position and rotation, and to measure random noise produced by the test piston-cylinders.

I. Computer with COMPASS
For Pressure Crossfloat Extension

J. Automates the Crossfloat System
Calculates effective area using the direct and base ratio methods and generates data files with all relevant data for each point taken.

Most of the main components defined in Figure 1 are standard DHI products. Two significant non-standard components are the software to run the crossfloat, and the device used to measure the difference in pressure between the two systems. Originally the plan was to measure the difference in pressure using DHI RPM4 transfer standards based on the success experienced by NIST and AIST [2] using Paroscientific transducers to measure the difference between hydraulic piston gauges. This technique was originally presented at the NCSL International Workshop and Symposium in August of 2002. In addition to the ability to automate, this technique was attractive because the transfer standards could simultaneously measure noise and parasitic changes in pressure, mainly from differences in piston position and rotation. But unfortunately the repeatability of the transfer standards, though sufficiently low enough to support the higher pressure hydraulic application, was too large of an influence for the uncertainty needed to support the effective area measurement of low pressure, gas lubricated piston-cylinders.

Instead of using transfer standards the decision was made to use a differential pressure transmitter. This made sense considering the requirement was for differential pressure measurement and a transmitter could provide more consistency at the various pressures used to determine effective area in the crossfloat. Knowing the output of transmitters can change when line pressures change, the external hardware was designed to be able to recalibrate zero and slope for each pressure point in the crossfloat test.

Originally it was not known whether or not it would be necessary to calibrate the slope of the transmitter at every point. In order to do this the transmitters had to have sufficient range to be calibrated by the chosen reference piston-cylinder. Since the resolution of an AMH mass set is 0.1 kilograms, the transmitter ranges had to support ±1, 5 and 20 kPa differential pressure measurement to support a slope calibration using the lowest mass available, 0.1 kg, loaded on the 10, 50 and 200 kPa/kg piston-cylinders respectively. As experience was gained it was determined that results were as good or better if the slope of the transmitter was not re-calibrated at every point. This is mainly due to the differential pressures being so small that they were not affected significantly by changing slopes and also it was predicted the pre-point slope calibration was introducing a significant hysteresis effect on the transmitter at the higher pressures. Because of this only the ±1 and 5 kPa ranges are used and the pre-point slope calibration was removed from the automated crossfloat procedure, and only the pre-point zero is performed.

The software controlling the system is COMPASS for Pressure software with non-standard activeX crossfloat extension. Figure 2 is a screen shot from the run screen of the COMPASS crossfloat extension.

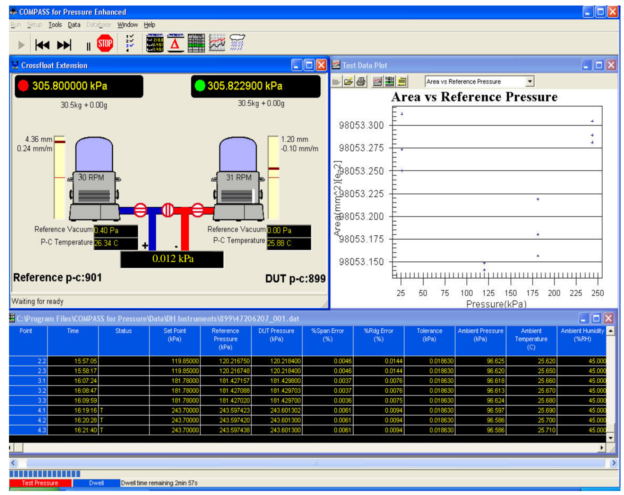

Figure 2. COMPASS crossfloat extension run display.

The COMPASS crossfloat extension is unique in that it can calculate effective area based on the direct and base ratio methods described earlier. Because of the nature of the calculations only the direct ratio results can be seen real time. Base ratio results, since they depend on the first and last point data, cannot be obtained until the crossfloat is completed. Comparison of the results of the two methods is advantageous in determining where errors originate, and builds confidence in the results when they agree.

On the srceen shown in Figure 2. are three sub views. On the upper left is a real time numerical and graphical indication of exactly what the crossfloat system is doing. Included are pressures and their ready state, drop rate and rotation rate, a graphical representation of piston position, a graphical representation of the valve states, the current pressure read by the differential pressure transmitter, vacuum pressures for the vacuum references and identification of the piston-cylinders in the test. To the right of the crossfloat sub view is a chart of the test effective areas determined by Direct Ratio method at each pressure that has been completed so far in the crossfloat. Underneath both of these are scrollable data fields where an observer may look at specific data being logged in the data file created by the crossfloat extension.

In addition to determining effective area, the software was written to perform automated performance testing of the test piston-cylinder. As stated earlier the RPM4s that were originally intended to measure the difference between the piston gauges were kept so that they could be connected and COMPASS would automate the testing.

4. RESULTS OF AUTOMATED CROSSFOLATS

Normally, only the Base Ratio results are used for the determination of the effective areas performed by the automated crossfloat system. The Direct Ratio results are useful because they show real time effective area results and can let an operator know when there are problems. However it was determined early in the project that the Base Ratio method would have lower uncertainties and more consistent results.

As mentioned in the section describing crossfloat methods, the Base Ratio method eliminates systematic errors and uncertainties contributed from the piston and weight carrier mass. In the manual method of a Base Ratio crossfloat the masses are permutated (exchanged) at each crossfloat point to effectively eliminate systematic errors introduced by the main mass set. For the automated crossfloat system this is not practical because the masses are isolated in the vacuum during the entire test. Instead of attempting mass permutations, the piston-cylinders are exchanged in the piston gauges and the crossfloat is performed again. The difference in the two effective areas determined in the two orientations exposes systematic errors introduced from the platforms and the masses used.

During the initial implementation of the crossfloat system all test piston-cylinder effective areas were determined in both orientations. The results were averaged to eliminate or reduce any systematic errors contributed by the platforms or masses. The original procedure for each piston-cylinder was as follows:

4.1 Perform 10 effective area crossfloats in the first orientation over night. Each crossfloat included six points plus one repeat of the first (base) point. Ranges are 40 to 380 kPa, 200 to 1900 kPa and 800 to 7000 kPa for 10, 50 and 200 kPa/kg piston-cylinders, respectively.

4.2 Perform 10 effective area determinations in the other orientation the next night using the same reference.

4.3 Perform a) and b) again on another piston-cylinder of the same range.

4.4 Close the loop… Perform an effective area comparison between the two test piston-cylinders with at least three runs in each orientation.

4.5 Test the performance of the piston-cylinder using the RPM4s.

4.6 Perform a verification in gauge, manual mode with another reference by comparing output pressures using the new determined effective area for the test piston-cylinder.

Table 1 represents the typical results attained when performing a crossfloat for a 10 kPa/kg piston-cylinder in one orientation. Each point is the average of three readings taken. The Base Ratio result is not included for the 42 kPa point since all the other points taken correct back to that first (base point). Figure 2 represents the same results, but for a larger set of data that includes all three ranges of piston-cylinders supported by the crossfloat system.

				Determined Area (20,0)		Ae Diff	Difference From Average	
Nom. Pressure	Trim Mass	Test Temp	Ref. Temp	Direct	Base	Base-Direct	Direct	Base
[kPa]	[g]	[°C]		[mm^2]		[ppm]		
42	-0.029	24.89	24.76	980.5230	---------		3.0	-------
104	-0.033	24.90	24.78	980.5210	980.5192	-1.7	0.9	0.7
166	-0.030	24.92	24.79	980.5199	980.5188	-1.1	-0.2	0.3
229	-0.024	24.93	24.81	980.5194	980.5186	-0.7	-0.7	0.1
291	-0.008	24.96	24.83	980.5188	980.5181	-0.7	-1.3	-0.5
353	0.002	24.99	24.86	980.5185	980.5179	-0.6	-1.6	-0.6
				Average				
				980.5201	980.5185			

Table 1. Ex. of Direct and Base Ratio results for one 10 kPa/kg crossfloat.

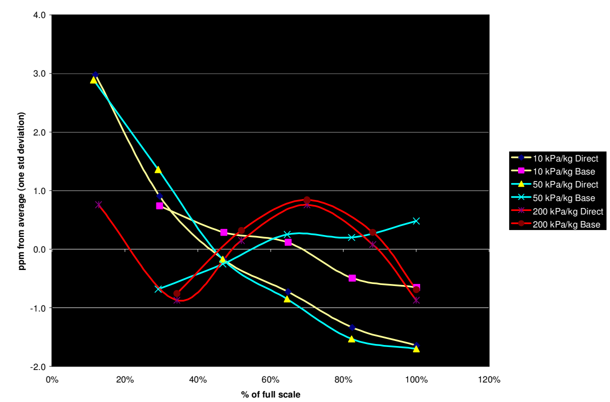

Figure 2. Ex. of Direct and Base Ratio comparison of all three ranges.

Figure 2 is only one (random) sample of each piston-cylinder range supported by the crossfloat system. The sample provides an indication of what was determined with a much greater amount of data. The effective area residuals, or apparent linearity, are consistently better with the Base Ratio results when compared to the Direct Ratio results. Its predicted the reason for the better results is the elimination of errors from the piston and weight carrier mass. However, either would have been acceptable to meet the target uncertainties of the effective area determination. Though it is not indicated in the sample given in Figure 2, the difference between effective areas determined by Direct and Base ratio methods did not exceed three parts per million. Note that the difference from average effective area from the example in Table 1 are also represented in Figure 2.

In the initial stages of the automated crossfloat system data was limited so performing ten crossfloats each night was advantageous. As consistent results were produced it was decided to reduce the number of runs performed each night to a minimum of three, and a maximum of five, successful crossfloats. The number of points taken in each crossfloat was not changed. Note that tests were normally only done at night to make available other tests during the day that required some manual setup or intervention.

By observing the difference of effective area of the same piston-cylinder in different orientations, systematic errors introduced by the platforms and main masses are exposed. With this information improvements and corrections on the platforms and mass sets reduced the systematic errors and increased confidence enough to allow effective areas to be performed in only one orientation. As a requirement, the next test piston-cylinder of the same range is tested in the other orientation. The two test piston-cylinders tested in separate orientations are compared to ensure there are no significant systematic influences.

Tables 2a, 2b and 2c are the results of all customer test piston-cylinders (with very few exceptions) calibrated by the automated crossfloat system from the time it was put into service through July of 2007. The tables identify:

- Date the test was performed.
- One standard deviation of the results of all crossfloats performed for that piston-cylinder for each orientation (O1 and O2)
- Difference in effective area between the two orientations, if tested in two orientations.
- Average error of all points tested in the manual gauge verification (average VOC error).

The expectation is that the deviations in the verification will be significantly larger than effective area deviations, but well within the uncertainty in pressure defined by the piston gauge. This is because the verification is a comparison in pressure, not just effective area, and are susceptible to all errors contributed by the piston gauge platform and mass sets. However the result is still a good indication whether or not there were significant systematic influences when the effective area was determined. An indication of this is in the first few rows of table 2a and 2c where orientation differences were significantly large. This was due to a known temperature error that had yet been resolved. However, the verification does not represent this systematic difference. This lends evidence that averaging the results for the two orientations eliminates systematic error contributed by the masses or the platforms.

Date Tested	Crossfloat Type A [ppm]		Orientation Error [ppm]	Average VOC Error [ppm]
	O1	O2	O2-O1	
11/9/2006	0.40	0.25	-13.60	-1.7
11/9/2006	0.70	0.41	-14.52	-0.9
11/9/2006	0.66	0.19	1.35	0.1
1/2/2007	0.36	---	---	-3.2
1/9/2007	0.57	---	---	-3.8
2/7/2007	0.21	---	---	-1.7
3/7/2007	0.42	---	---	-3.9
3/7/2007	0.25	---	---	-0.1
3/29/2007	0.42	---	---	-2.7
4/5/2007	0.27	---	---	-2.3
4/13/2007	0.30	---	---	-1.5
4/13/2007	0.36	---	---	-5.4
4/26/2007	0.36	---	---	4.5
5/1/2007	0.23	---	---	-4.7
5/22/2007	0.31	---	---	-0.4
6/1/2007	0.13	---	---	-1.2
6/1/2007	0.40	---	---	-3.6
6/1/2007	0.80	---	---	-2.5
6/27/2007	0.64	---	---	0.6
6/27/2007	0.54	---	---	---

Table 2a. Results of 50 kPa/kg effective area determinations

Date Tested	Crossfloat Type A [ppm]		Orientation Error [ppm]	Average VOC Error [ppm]
	O1	O2	O2-O1	
2/7/2007	0.53	---	---	-3.3
3/7/2007	1.19	---	---	-8.1
3/7/2007	0.36	---	---	-6.9
3/9/2007	0.38	---	---	-2.9
4/7/2007	0.56	---	---	-3.6
4/13/2007	1.60	---	---	7.8
4/13/2007	0.40	---	---	2.1
4/18/2007	0.53	---	---	2.0
4/26/2007	0.48	---	---	1.5
6/1/2007	1.91	---	---	4.6
6/14/2007	0.95	---	---	6.6
6/14/2007	1.25	---	---	5.1
6/27/2007	0.33	---	---	1.5
6/27/2007	0.32	---	---	7.7
7/18/2007	0.75	---	---	0.1
7/30/2007	1.95	---	---	6.8
7/30/2007	1.29	---	---	3.9
7/30/2007	1.05	---	---	6.0
7/30/2007	0.00	---	---	-1.0

Table 2b. Results of 200 kPa/kg effective area determinations

Date Tested	Crossfloat Type A [ppm]		Orientation Error [ppm]	Average VOC Error [ppm]
	O1	O2	O2-O1	
12/12/2006	1.2	1.3	10.7	---
12/12/2006	0.8	0.6	15.8	---
12/12/2006	0.3	0.1	15.1	-3.9
12/12/2006	0.7	0.5	14.7	-4.5
1/9/2007	0.4	---	---	2.5
1/9/2007	0.3	1.2	14.6	-1.2
2/7/2007	0.8	---	---	-1.5
2/7/2007	0.9	---	---	-2.3
2/23/2007	0.6	---	---	-3.3
3/7/2007	0.6	---	---	-2.5
3/7/2007	0.5	---	---	3.8
3/9/2007	0.6	---	---	-1.4
3/19/2007	0.1	---	---	0.0
4/13/2007	1.1	---	---	-2.1
4/13/2007	0.5	---	---	-2.2
4/18/2007	1.1	---	---	-3.7
5/7/2007	0.2	---	---	1.8
5/16/2007	0.3	---	---	1.8
5/22/2007	0.4	---	---	2.3
5/23/2007	0.3	---	---	-6.2
6/6/2007	0.8	---	---	-1.7
6/6/2007	0.4	---	---	1.8
6/6/2007	0.1	---	---	-0.6
6/6/2007	0.4	0.4	2.1	-2.5
6/6/2007	0.5	0.4	2.5	3.2
6/6/2007	1.4	0.4	-2.6	-1.6
6/27/2007	2.8	---	---	-1.9
6/27/2007	0.8	---	---	0.5
6/27/2007	1.7	---	---	-0.9
6/27/2007	0.5	---	---	-4.6

Table 2c. Results of 10 kPa/kg effective area determinations

In Table 2c there is data from three effective area determinations performed on June 6, 2007 that were completed in both orientations. These were DHI working references where even small systematic uncertainty contributions were not desirable.

Tables 2a, 2b and 2c include all effective area determinations performed on the automated crossfloat system from November of 2006 through July of 2007, equaling roughly 70 piston-cylinders. It is estimated that the total technician time saved during this period is 400 hours (10 standard work weeks). In addition to the time saved, the precision is improved due the systematic nature of an automated system vs. the non-systematic nature of a technician performing manual crossfloats in gauge mode that are susceptible to air currents. This is enhanced by the fact that the expertise to run the automated crossfloat station is not nearly as demanding as manual crossfloats allowing for much easier cross training. Finally the automated crossfloat system could easily have completed almost twice as many effective area determinations considering it was not normally used in the day time.

As stated earlier, a unique characteristic of this process is that the effective area is determined in absolute mode and the verification is performed in gauge mode. The difference in effective area between absolute and gauge mode has been evaluated theoretically, but has never been evaluated extensively with crossfloats. Though the precision of the verification data taken in gauge mode for a single point is probably not sufficient to determine a difference between the two modes of use, an average of all the verification results for each piston-cylinder range should show if there is a systematic difference between using a piston gauge in absolute mode and using it in gauge mode. Table 3 shows the averages and two standard deviations of the mean of all the verification data taken in gauge mode. The conclusion is that there is not a significant systematic difference in effective area when it is used in gauge or absolute mode.

	10 kPa/kg	50 kPa/kg	200 kPa/kg
Deviation	-1.1	-1.8	1.6
Two std deviations of the mean	1.0	1.0	2.2

Table 3. Difference between gauge and absolute piston gauge operation

5. CONCLUSION

The automated crossfloat system has improved both yield and precision of the effective area determinations performed at DHI. The success of this project has opened the door for other types of automated crossfloat systems, such as higher pressure gas and oil media crossfloats, and will be important tool in realizing lower uncertainties for future DHI pressure calibration chains.

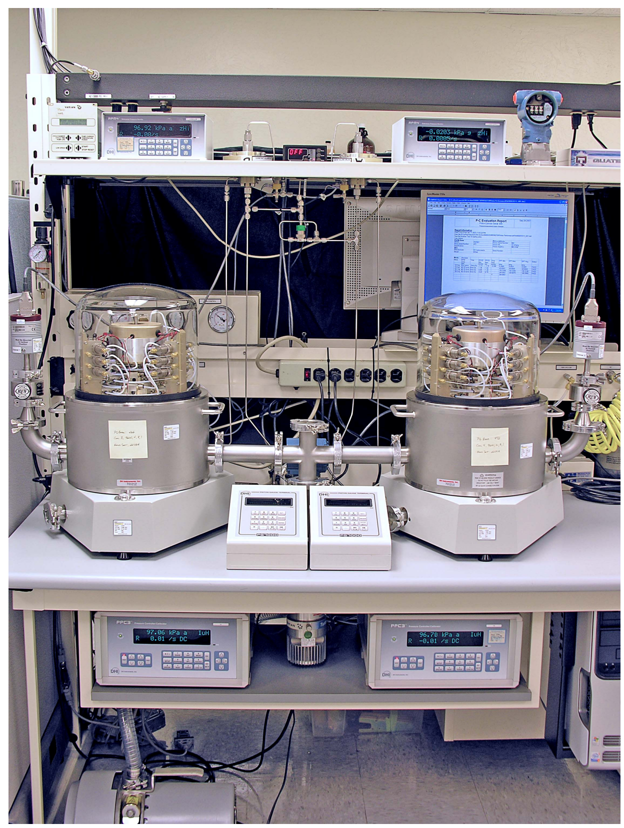

Figure 4. Picture of the automated crossfloat system at DHI

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LIST OF VARIABLES

$A_{e\ test}$	Effective area of the test piston-cylinder
$A_{e\ ref}$	Effective area of the reference piston-cylinder
m_{test}	Total true mass on the test.
m_{ref}	Total true mass on the reference
g_l	Local acceleration of gravity
T_{norm}	Reference temperature
P_{test}	Pressure defined by the test piston gauge
P_{ref}	Pressure defined by the reference piston gauge
λ_{ref}	Theoretical elastic deformation of the reference piston-cylinder
λ_{test}	Theoretical elastic deformation of the test piston-cylinder
ρ_{air}	Density of air
ρ_{mtest}	Density of mass on test
ρ_{mref}	Density of mass on reference
ρ_f	Density of operating fluid
γ	Surface tension
C_{test}	Circumference of test piston
ε	Mass adjustment to equalize piston gauge output
C_{ref}	Circumference of reference piston
$\alpha_{c\ ref}$	Thermal expansion coefficient of reference cylinder
$\alpha_{p\ ref}$	Thermal expansion coefficient of reference piston
$\alpha_{c\ test}$	Thermal expansion coefficient of test cylinder
$\alpha_{c\ test}$	Thermal expansion coefficient of test piston
$T_{\ ref}$	Temperature of reference piston-cylinder
$T_{\ test}$	Temperature of test piston-cylinder
h	Difference in height between reference and test piston gauge reference levels