Static Gravimetric Method with Flying Start-and-Finish for Calibration of Small Hydrocarbon Flow

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Abstract

Static gravimetric method with flying start-and-finish is widely used for calibration of large and medium liquid flow for its advantage of maintaining continuous flow through the flowmeter. However one needs to take certain considerations in implementing this method in small flow systems to obtain good accuracy. At NMIJ, we adopted this calibration method for small hydrocarbon flow facility using newly designed diverting systems. This paper discusses the design features of a gravimetric system using a compact conical double-wing rotating diverter. Performance of the gravimetric system is also discussed, giving focus to the timing error of the diverting system and evaporation rate of the weighing tank.

1. Introduction

To provide measurement traceability for flow metering in industrial practices such as measurement of engine fuel consumption, household fuel consumption and blending of bio-fuel with petrol, development of a calibration facility as a primary standard for small liquid hydrocarbon flow was initiated at NMIJ. The development work has been carried out carefully by stages [1~4] and full-fledged calibration service covering the whole targeted flow range of 0.02 L/h ~ 100 L/h was achieved in 2015 [5].

In the first design of the facility, static gravimetric method with standing-start-and-finish was chosen as the calibration method because it eliminated the diversion uncertainty and made the calibration system simpler and economical without a diverter system. However, as widely known, standing-start-and-finish introduces variation of flow rate during ramp up and down of flow by valve opening and closing. This may cause calibration error especially for flowmeters with non-linear characteristics or having slow response to flow variation due to damping factors or having a low flow cut-off setting. We performed a special procedure to evaluate this calibration error that might occur and introduced it to the uncertainty of the final calibration results [3].

To benefit from the advantage of flying-start-and-finish which maintains a constant flow rate throughout calibration, we shifted to this calibration method by incorporating diverting systems into the gravimetric systems of the facility. The facility has two gravimetric systems, one for the upper flow range (1 L/h ~ 100 L/h) and another for the lower flow range (0.02 L/h ~ 1 L/h), each equipped with different weighing scale, to facilitate efficient liquid collection especially in low flow ranges. This paper will discuss on the gravimetric system for the upper flow range which incorporated a compact conical double-wing rotating diverter.

2. Existing diverter systems at NMIJ

Various types of diverter systems are being used for flying-start-and-finish method, especially in large and medium flow systems. Single wing diverter (SWD) was the earliest design used for large water flow calibration facility at NMIJ [6].

To reduce diverter timing error due to flow profile distortion as encountered in single wing systems, double wing diverter (DWD) based on symmetrical diverting principle that makes the diverter timing error insensitive to flow profile distortion, was proposed [7] and adopted into large hydrocarbon flow facility [8] at NMIJ. Later, to solve the inefficiency in implementing ISO4185 test [9] on double wing diverter with linear motion, rotating double wing diverter (RDWD) was proposed [10] and employed in medium hydrocarbon flow facility [11] at NMIJ.

3. Design of a new gravimetric system using a diverter

Tapping on the advantages of DWD and RDWD, we attempted to design a gravimetric system using a diverter which is suitable for low and evaporative flow rates. We figured out a gravimetric system, as illustrated in Figure 1, that comprises a conical rotating double-wing diverter (CRDWD), a rectangular weighing tank sitting on a weighing scale and a liquid discharge mechanism using a suction nozzle. Features of each component and the designing considerations behind them will be described in the following sections.

3.1 Conical rotating double-wing diverter

This newly designed diverter is based on the symmetric diversion principle introduced by Shimada et al. [7], and works by rotary motion as proposed by Doihara et al. [10], but is improved in terms of structural design to make it more compact and suitable for operation at low flow rates. This new diverter has two wings moving in the same direction at constant speed across the liquid jet to perform symmetric diversion, a common characteristic with DWD. The diverter rotates in the same direction around the center axis of the cone which runs parallel to the liquid jet flowing vertically downward. This rotating mechanism similar to RDWD makes it a simple and robust structure, easing the implementation of ISO4185 test and adjustment of trigger timing.

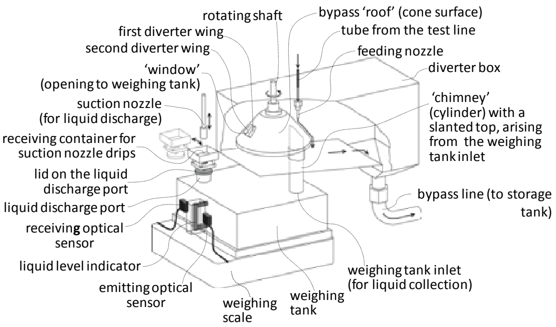

Figure 1: A new gravimetric system using conical rotating double-wing diverter (CRDWD); CRDWD at $0^o/360^o$ position (diverter's window on the opposite side from feeding nozzle).

In low-flow calibration, amount of liquid collection is unavoidably set small to cut down the collection time. Hence, error due to liquid residue at the wings' wall occurring when liquid jet comes into contact with the diverter wings as well as error due to liquid evaporation from the weighing tank become relatively significant as amount of liquid collection is made smaller. This leaves room for improvement to the existing diverter designs and necessitates downsizing and modifications to make the new diverter more compact and more invulnerable to such errors. These criteria led us to the present design, as shown in Figure 1, which is characterized by a conical structure with a small window (opening) on the cone surface and two wings protruding from both sides of the window. The window leads the liquid jet into the weighing tank while the rest of the cone surface acts as the bypass sloping 'roof', letting the liquid to flow down its surface with little splashing and head towards the exit of the diverter box. This small window of the diverter combined with special features of the weighing tank (to be described in the next section) is deemed to be effective for cutting down vapor escape. Moreover the diverter is placed inside the enclosure of a diverter box in order to make the air saturated for minimizing evaporation. The diversion wings take the shape of a double-edged blade and have small wet area. Moreover they are coated with special coating (which is 'hydrophobic' for oil) to accelerate the running down of liquid from the wings' surface. All these measures make the liquid residue on the wings' surface to be considerably reduced.

3.2 Weighing tank

As indicated in Figure 1, the weighing tank is made rectangular to fit the shape of the weighing plate so that it can sit stably on it. One of the special features of the weighing tank is a chimney-like cylindrical structure, standing upright from the inlet of the weighing tank. To receive liquid jet coming through the diverter's window, this 'chimney' is placed right below the window with its slanted top nearing the window opening but not too near to avoid any contact. Moreover the 'chimney' top has a cross-sectional area that is slightly bigger than that of the window so that all liquid drops into it. This thin 'chimney' combined with the small diverter window is considered to be effective in reducing evaporation during liquid collection.

Liquid has to be discharged from the weighing tank after each liquid collection and this is actually a tedious task to be done manually without automation. To prepare for automated discharging, the weighing tank is equipped with a discharge port with a lid on it (see Figure 1). This lid has a special knob so that it can be lifted up from and placed down to the discharge port by simple actuation. The discharge port is purposely provided with a lid to avoid vapor escape. The next section will explain in more details how the lid is moved by the discharging mechanism.

Operational safety is another important factor to be considered and to make the weighing tank fail-safe to overflow during liquid collection, it is equipped with a liquid level indicator under the scrutiny of a pair of optical sensors (emitting and receiving sensors). These optical sensors also make no contact with the weighing tank. Once a dangerous liquid level is detected, the control system is alerted to terminate liquid collection by rotating the diverter's window away from the weighing tank's 'chimney'.

3.3 Liquid discharge mechanism

Normally weighing tanks in large and medium flow systems are equipped with discharging valves which are actuated pneumatically. But pneumatic valve usually takes space and possesses considerable weight, hence making it difficult to be fitted on a small weighing tank. It also usually takes time for all the liquid to leave the tank through the valve though some liquid will still remain in the tank's bottom. Moreover the air supply and power connections exert certain tension and may cause error to scale readings, especially for smaller weighing scale which is more sensitive as a result of higher weighing resolution. Another disadvantage is the possibility of leakage which requires regular leakage check of discharging valves and the pipework. Moreover liquid residue that gradually drips off the pipework also poses a source of error to the scale reading.

Considering the factors above, we opted for a liquid discharging method using a suction nozzle connected to a discharging pump, which we expected to be simpler, more direct and faster. However things turned out to be not so simple and we had to take certain measures to make sure that the discharging mechanism work out nicely in a clean and effective manner. One of the problems is liquid dripping from suction nozzle. A small amount of liquid will always remain in the suction nozzle and if they drip on the weighing tank, this will cause error and make the place dirty. To solve this, we considered a way by making the movement of the suction nozzle simple, just up and down vertically on top of the weighing tank's discharge port (see Figure 1). By doing this, the liquid drips only fall onto a limited area and can be easily collected by a receiving container. As shown in Figure 1, a receiving container is mounted on top of a lifting mechanism that moves the lid away and back to the discharge port, so that the receiving container moves together with the lid by sharing the same actuator. Meanwhile, the suction nozzle moving only in vertical direction is operated by another actuator, independent from that of the lifting mechanism. Like this, consisting of only two actuator systems, we made the liquid discharging mechanism as simple as possible.

The three components described in the sections above – diverter, weighing tank and liquid discharge mechanism – have to be put together, complementing one another in working as an effective gravimetric system.

4. Operation of gravimetric system

In this section, how the three components of the gravimetric system work together in an automated operational sequence will be described by referring to the diagrams given in Figure 2.

As shown by Figure 2(a), liquid flows through the feeding nozzle and bypasses at the diverter before heading towards the exit of the diverter box. At this moment, the gravimetric system is on standby for liquid collection. Diverter's window is on the opposite side from the feeding nozzle (0^o position); weighing tank is empty; and liquid discharge port is covered by lid. Reading of the weighing scale with an empty tank is recorded before liquid collection begins.

To begin liquid collection, the diverter makes a half-turn, rotating its window towards the feeding nozzle (180^o position), stopping at where the feeding nozzle is positioned at the center of the window. During the half-rotation, the first diverting wing on one side of the window traverses the liquid jet, marking the start of the liquid collection. At this juncture, starting of liquid collection time measurement is triggered. Operation state of the gravimetric system in which liquid is being accumulated inside the weighing tank is shown in Figure 2(b).

When amount of liquid collection reached the value set, the diverter makes another half-turn in the same direction, bringing the window back to its original position (0^o or 360^o position). In this second half-turn, the second diverting wing on the other side of the window cuts across the liquid jet, ending the liquid collection. At this instant, the measurement of liquid collection time is triggered to stop. Liquid bypasses at the diverter again. Reading of the weighing scale with a filled tank is recorded. Figure 2(c) shows the state of the gravimetric system at this moment.

Finally, as shown in Figure 2(d), the liquid discharging mechanism moves into action, by first lifting away the lid from the discharge port, followed by descent of suction nozzle into the discharge port before beginning the discharging. Once the weighing tank becomes empty, the suction nozzle and the lid are moved back to their respective original position and this brings the gravimetric system back to 'standby' in Figure 2(a). This completes one cycle of liquid collection and this cycle is repeated according to the number of calibration runs.

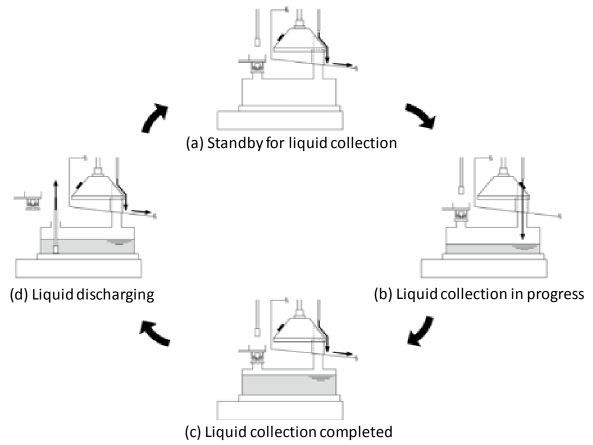

Figure 2: Operation sequence of gravimetric system.

5. Performance of gravimetric system

5.1 Diverter timing error

Uncertainty of liquid collection time depends on the timing error of the diverter. Diverter timing error was estimated experimentally according to one of the methods recommended in ISO4185 [9]. The estimation method comprises two diversion procedures: (i) a single diversion (one long diversion) and (ii) a series of short diversions. First, the weighing tank is filled up by a single diversion to obtain one liquid collection, m_1, and time duration of one long diversion, t_{D1}. Next, the weighing tank is filled up by a series of n short diversions without resetting the weighing scale and timer to obtain the total liquid collection $\Sigma_{i=1}^{n} m_i$ and total diversion time $\Sigma_{i=1}^{n} t_i$. From these, timing error Δt is obtained as follows:

$$\Delta t = \frac{t_{D1}}{n-1}\left(\frac{q_1}{q_n}\cdot\frac{\Sigma_{i=1}^{n} m_i / \Sigma_{i=1}^{n} t_i}{m_1 / t_{D1}} - 1\right) \qquad (1)$$

Here, q_1 represents the flow rate during a single diversion measured by a flowmeter, and q_n is the average of the flow rates measured by the flowmeter during n diversions.

In the gravimetric system at NMIJ, angular position of the diverter is determined by a rotary encoder. Before ISO4185 estimation test is carried out, angular positions at which the first and second diversion wings traverse the center of the feeding nozzle were determined and these correspond to the angular positions for transmitting 'start' and 'stop' trigger signals for diversion time measurement. From the initial ISO4185 estimation test, a timing error Δt was obtained. By multiplying the angular velocity of the diverter $\delta\theta/\delta t$ against the timing error Δt , adjustment angle $\Delta\theta$ for the trigger signals was derived. After adjusting the angular positions electronically (i.e. key entry of new angular positions into the diverter control system), ISO4185 estimation test was performed again to obtain a new timing error. These procedures were repeated until the timing error became satisfactory. Meanwhile, angular velocity of the diverter was set at a constant value of 540^{o} /s, corresponding to wing speed of about 0.45 m/s.

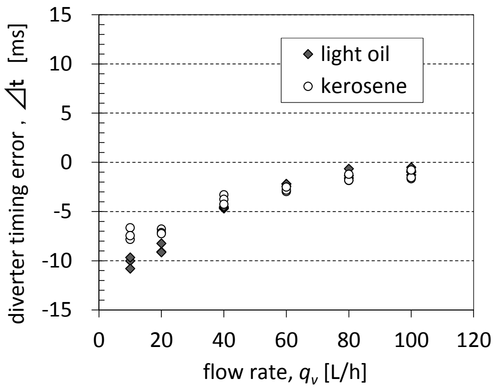

Figure 3: Diverter timing error of two diverters (after adjustment) using feeding nozzle with inner diameter of 4 mm. ◆: diverter for light oil, ○: diverter for kerosene.

The facility has two flow circuits running on light oil and kerosene respectively. Each flow circuit is equipped with its own diverter system. Figure 3 shows the diverter timing errors for each of the diverter system after adjustment. The abscissa indicates the flow rate and the ordinate denotes the timing error. As can be observed from Figure 3, timing errors at higher flow rates (80 ~ 100 L/h) are within -2 ms and gradually become larger, reaching -10 ms ~ -7 ms at 10 L/h. This is contrary to the common characteristic of double-wing diverters whose timing error is independent of flow rate and normally remains constant against varying flow rates [7, 10].

To investigate the reason for the dependency of timing error on flow rate, we made an observation of the jet flow behaviour during diversion wing's traverse by positioning the diversion wing right below the feeding nozzle. In the timing error estimation test, feeding nozzle with an inner diameter of 4 mm were used for both diverters. As the flow rate decreased, the liquid jet velocity coming out from the nozzle became lower. As shown in Figure 4(a), jet flow at low velocity tends to veer away from the straight path when it flows down the wing's surface, converging and running down along the bottom edge of the wing blade. This jet flow behaviour caused a reduced liquid collection during flow diversions and made the timing error become negative. As the flow rate (flow velocity) became smaller, deviation of jet flow away from the straight descending path on the wing's surface into the weighing tank became more significant, resulting in larger timing errors.

To see how the jet flow behaves at high velocity, we replaced the feeding nozzle with one that has smaller inner diameter (1 mm) and made an observation by setting the same flow rate (10 L/h in this case) with Figure 4(a). What we observed is shown in Figure 4(b) where the liquid jet at high velocity flows down the wing's surface without deviation into the weighing tank. This should ensure a satisfactory liquid collection and consequently reduce the timing error. A timing error estimation test at a flow rate of 10 L/h using the feeding nozzle with 1 mm inner diameter confirmed this. Average of diverter timing errors obtained using the small nozzle is about -1.2 ms for light oil diverter and -1.3 ms for kerosene diverter, showing little difference with the average of timing errors (light oil: -1.0 ms, kerosene: -1.5 ms) obtained for higher flow rates (80 ~ 100 L/h) using a bigger nozzle (inner diameter 4 mm). This consistency of diverter timing error against the varying flow rates confirms that higher jet velocity yielded by the small diameter of the nozzle made the jet flow along the wing's surface to be more directed with little deviation, hence enabling the double-wing diverter to retain its performance at low flow rate.

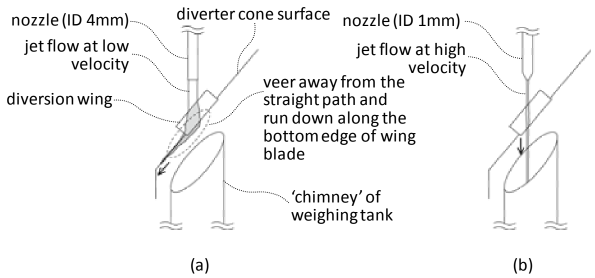

Figure 4: Jet flow behaviour along the surface of diversion wing. (a) Deviated flow path (flow rate 10 L/h, nozzle inner diameter 4 mm). (b) Straight flow path (flow rate 10 L/h, nozzle inner diameter 1 mm).

5.2 Evaporation of weighing tank

To evaluate the effectiveness of the gravimetric system in reducing evaporation, an experimental observation was made on the liquid weight loss in the weighing tank. Since there is no ideal way of investigating the actual evaporation rate during liquid collection, we had to resort to an approximation method. There are two approximation methods thinkable: one method is by filling up the tank and seeing the weight changes after the fill-up; another method is done by first filling up the tank, then discharging the liquid from the tank followed by monitoring the weight change of the remaining liquid in the tank.

In actual practice, as a preparatory step, at least one liquid collection (a trial run) is performed before actual calibration runs are conducted. Therefore liquid discharging usually precedes liquid collection. Emptying the tank induces intake of fresh air into the tank, diluting the vapor saturation level in the tank. This may result in higher evaporation rate at the start of liquid collection. Vapor saturation level may recover as liquid is being accumulated in the tank, consequently slowing down the evaporation rate. However other factors including ambient conditions such as room temperature and air movement also influence the evaporation rate. Considering these, of the two approximation methods mentioned above, we opted for the latter one.

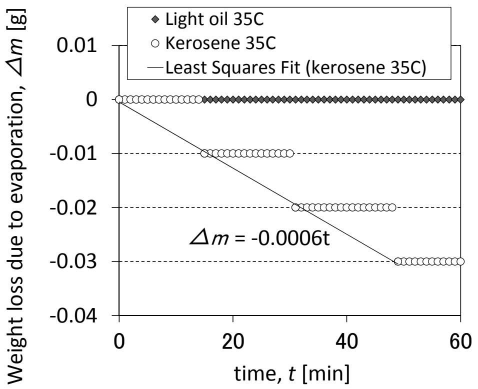

Figure 5: Weight loss due to evaporation over time (liquid temperature 35°C).

Liquid temperature at this facility can be set from 15°C to 35°C depending on calibration conditions. Using the second approximation method as described above, we investigated the evaporation rate of the two gravimetric systems for light oil and kerosene respectively, under the most evaporative conditions in which liquid temperature was set at 35°C and measurement room temperature was set at 30°C. After emptying a full tank, we monitored the weight change from the initial weight reading for an hour. As shown in Figure 5, reading of weighing scale for light oil remains constant over an hour, indicating the evaporation rate of light oil was very low to the extent that was undetectable by the weighing scale resolution of 0.01 g. On the other hand, reading of weighing scale for kerosene decreases steadily, showing a weight loss of 0.03 g over an hour. By a rough observation, the evaporation rate was about -0.02 g in the first half-an-hour and slowed down to about -0.01 g in the second half-an-hour. Making a least squares fit by taking the steepest gradient, we can observe that kerosene at 35°C evaporates at a rate of 0.036 g/h (0.0006 g/min). Making a liquid collection for one hour at a low flow rate, for instance 1 L/h of kerosene, results in weight collection of about 780 g (relative density of kerosene at 35°C is about 0.78). Dividing the weight loss based on evaporation rate by least squares fit with the weight collection, contribution of evaporation effect in terms of uncertainty is derived as about 0.005 %. We also investigated the evaporation rate of light oil and kerosene at a lower liquid temperature of 20°C, obtaining evaporation rates of below 0.01 g/h for all cases. Therefore, the gravimetric system is confirmed to be effective in reducing evaporation effect to a negligible level even for long liquid collection time at low flow rates.

6. Conclusions

This paper discusses the features of a new gravimetric system employing flying-start-and-finish method for small liquid hydrocarbon flow facility at NMIJ. Discussion has been made on the features of main components of the gravimetric system, namely the conical rotating double-wing diverter, the weighing tank and the liquid discharging mechanism, explaining the design considerations behind each feature.

The conical rotating double-wing diverter, besides inheriting the advantages of double-wing principle and rotational motion of past diverters [7, 10], features an umbrella-like conical main structure with a small window and two downsized diversion wings to overcome the problems of residual liquid and evaporation in low-flow measurement. The chimney-like structure of weighing tank complements the small window of diverter in reducing evaporation rate whereas the discharge port of weighing tank, equipped with a moveable lid, facilitates liquid discharging by suction nozzle. The liquid discharging mechanism based on liquid suction has special features for clean and effective discharging, easy and economical automation, and most importantly preventing error due to liquid drips for measurement accuracy. The authors stress that the three components described above have to be put together to complement one another in working as an effective gravimetric system.

Performance tests show that diverter timing error can be reduced satisfactorily at any flow rates as long as the jet flow velocity is kept high enough by using feeding nozzles with suitable diameter sizes. Weight loss due to evaporation is sufficiently small even for long liquid collection under evaporative conditions. All these confirm the gravimetric system's capability in performing low and evaporative flow calibration.

References

[1] Cheong KH, Shimada T, Doihara R, Terao Y, Takamoto M, A new calibration facility for small flow of hydrocarbon liquid, In: Proceedings of 15th International Conference on Flow Measurement (15th FLOMEKO), paper no. 60, Taipei, Taiwan, 2010.

[2] Cheong KH, Shimada T, Doihara R, Terao Y, Takamoto M, Development of a calibration facility for small hydrocarbon flow as a national standard, In: Proceedings of 5th International Symposium on Experimental Mechanics (5th ISEM) , paper no. 73, Kyoto, Japan, 2010.

[3] Cheong KH, Doihara R, Shimada T, Terao Y, Improvement to small hydrocarbon flow calibration facility at NMIJ, In: Proceedings of 8th

International Symposium on Fluid Flow Measurement (8th ISFFM), Colorado Springs, USA, 2012.
[4] Cheong KH, Furuichi N, Doihara R, Shimada T, Terao Y, In-house comparison between small hydrocarbon flow facility and small water flow facility at NMIJ, In: Proceedings of 16th International Conference on Flow Measurement (16th FLOMEKO), Paris, France, 2013.
[5] Cheong KH, Doihara R, Shimada T, Terao Y, Expansion of calibration flow range of small liquid hydrocarbon flow facility at NMIJ, In: Proceedings of 9th International Symposium on Fluid Flow Measurement (9th ISFFM), Washington DC, USA, 2015.
[6] Terao Y, Takamoto M, Uncertainty analysis of large water flow calibration facility, In: Proceedings of the 4th International Symposium on Fluid Flow Measurement (4th ISFFM), Denver, Colorado, USA, 1999.
[7] Shimada T, Oda S, Terao Y, Takamoto M, Development of a new diverter system for liquid flow calibration facilities, Flow Measurement and Instrumentation, 14 (2003) 89–96.
[8] Shimada T, Doihara R, Terao Y, Takamoto M, Stolt K, Andersson A, New primary standard for hydrocarbon flowmeters at NMIJ - International comparison between NMIJ and SP, In: Proceedings of 11th International Conference on Flow Measurement (11th FLOMEKO), paper no. 111, Groningen, Netherlands, 2003.
[9] The International Organization for Standardization. Measurement of liquid flow in closed conduits - weighing methods. 1st ed. International Standard. ISO 4185; 1980.
[10] Doihara R, Shimada T, Terao Y, Takamoto M, Development of weighing tank system employing rotating double wing diverter, Flow Measurement and Instrumentation, 17 (2006) 141–152.
[11] Doihara R, Shimada T, Terao Y, Takamoto M, Development of the national standard facility for hydrocarbon flow at 0.1 to 15m^3/h, In: Proceedings of 14th International Conference on Flow Measurement (14th FLOMEKO), Sandton, South Africa, 2007.