FLOMEKO2019
18th International Flow Measurement Conference
Portugal | Lisbon | LNEC | 26-28 june 2019

A New Gravimetric Primary Standard for Natural Gas Flow Measurement at KOGAS

Young-Cheol Ha[1], Myoung-Seok Kwak[1], Woong Kang[2]

[1] *Korea Gas Corporation (KOGAS), 950 Incheonsinhangdea-ro, Incheon 21993, South Korea*
[2]*Korea Research Institute of Standards and Science (KRISS), Daejeon 34113, South Korea*
E-mail (corresponding author): fractals@kogas.or.kr

Abstract

A new static gravimetric primary standard facility, which was constructed at the Incheon LNG terminal of Korea Gas Corporation (KOGAS) in 2017, is currently operated at pressures up to 5 MPa. Its main tasks include calibrating the secondary flow standard of the KOGAS high-pressure calibration facility (closed-loop type) and establishing the national primary standard for high-pressure natural gas flow measurement. To these aims, 1) the systematic error, which occurred due to an overlap diverter and has not yet been identified, was experimentally estimated for this facility, and 2) an inter-laboratory comparison between KOGAS and Korea Research Institute of Standard and Science (KRISS) was performed using five critical flow Venturi nozzles in 2018. Consequently, the systematic error was estimated to be about 0.06 %, and the degree of equivalence between KOGAS and KRISS was evaluated to be within ±0.23. The paper describes the standard facility and the comparison results.

1. Introduction

A new static gravimetric primary standard facility, which was constructed at the Incheon LNG terminal of Korea Gas Corporation (KOGAS) in 2017, is currently operated at pressures up to 5 MPa.

The standard facility is intended to establish the national primary standard for high-pressure (HP) natural gas (NG) flow measurement. One of its main tasks is to calibrate the secondary flow standard (i.e., the critical flow Venturi nozzles (CFVNs)) of the KOGAS HP calibration facility (closed-loop type) [1] and to prove its own accuracy. To achieve this aim, 1) the effects of an overlap diverter, especially for the systematic error, were estimated for this facility, and 2) an inter-laboratory comparison between KOGAS and Korea Research Institute of Standard and Science (KRISS) was performed using five CFVNs in 2018. The comparison was carried out at NG pressures of 1 MPa and 3 MPa (which are among the three calibration pressures of KOGAS's CFVNs), but not at 5 MPa. This is because the maximum pressure of the KRISS primary air-flow standard is 4 MPa, which is only 3 MPa in terms of NG Reynolds number under choked flow conditions. However, as the calibration method and procedure for CFVNs at 1 MPa and 3 MPa are identical to those at 5 MPa, the comparison results at both pressures can cover the measurement results at 5 MPa. This paper describes the standard facility and the comparison results.

2. Description of the standard facility

2.1 Design and operation

Figure 1 shows a schematic of KOGAS's static gravimetric flow standard facility and Table 1 provides its specifications. The standard facility consists of a flow supply system, pressure control valves, and a standard system that includes various pressure and temperature sensors, a gas chromatograph, a molar mass meter, a flow diverter (pinion-rack type) with overlapping valves, a collection tank, and a weigh scale.

For generating and stabilizing gas flow from 10 m^3/h to 170 m^3/h at pressures up to 5 MPa, the flow supply system has three HP storage tanks with a total volume of 140 m^3, two low-pressure (LP) storage tanks with a total volume of 58 m^3, a set of three pressure control valves that are arranged in parallel, and one measuring section with nominal diameter of DN 100 mm. For the diameter (*D*) of the measuring section, the upstream straight pipe length of the CFVN is more than 30 *D*. The 10 *D*

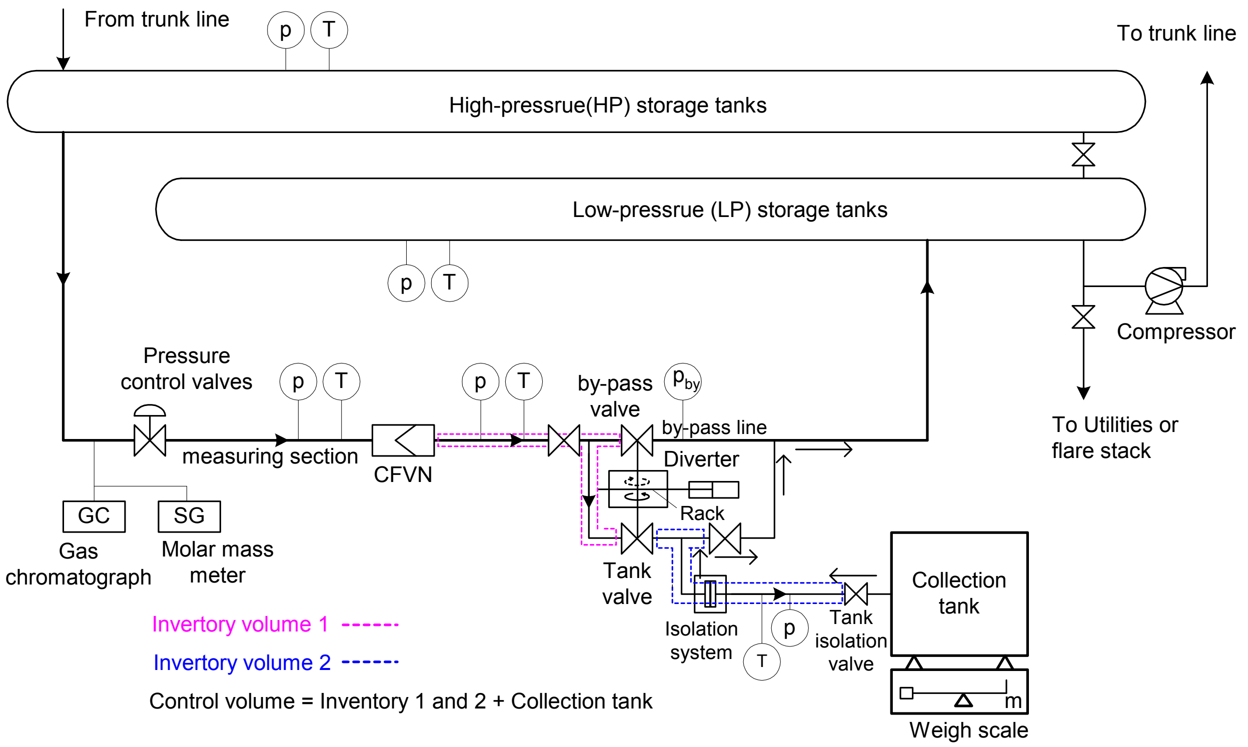

Figure 1: Schematic of the standard facility.

upstream pipe of the CFVN is made of stainless steel, while the inner surface, pressure wall taps and temperature sensor holes were carefully machined according to ISO 9300 [2]. The pressure in the measuring section is adjustable from 0.5 MPa to 5 MPa using the pressure control valves, and the pressure stability is maintained relatively well during a collection time due to the large volume of the HP storage tanks.

The process of making the gravimetric flow measurement entails the following steps:

1) Evacuate the gas in the collection tank down to atmospheric pressure.
2) Wait for pressure and temperature conditions in the collection tank to stabilize, and then measure the initial mass of gas in the collection tank.
3) Connect the collection tank to the piping using the isolation system (see Figure 1).
4) Establish a stable flow through the CFVN with flow going through the bypass valve.
5) Start the initial diversion for the flow into the collection tank and start the registration of the outputs (i.e., pressure, temperature, gas composition, and molar mass of gas) of the CFVN. At the same time, measure the pressures and temperatures in inventory volume 1 and 2. A collection start time is obtained at an accurately predetermined trigger point (see subsection 2.3) in the diverter-rack travel path because the diverter valves (i.e., bypass and tank valves, see Figure 1) is operated with valve overlap (hereafter 'overlap diverter'), i.e., one valve begins to open before the other is fully closed.
6) Wait for the tank fill to a prescribed upper pressure,

Table 1: Specification of the standard facility.

Figures	Provisions	Parameters
Operation mode	Blow down, fluid flow via HP and LP storage tanks	Three HP storage tanks of a total volume of 140 m^3; two LP storage tanks of a total volume of 58 m^3
Calibration method	Static gravimetric method, i.e. time-mass method	100 kg weigh scale with resolution 2 g; 3.09 m^3 collection tank; counterbalancing the tare weight of the collection tank; flow diverter with its valves overlapping
Medium	Natural gas (regasified LNG)	Concentration of inert gas less than 1 mol %
Flow ranges		10 m^3/h to 170 m^3/h
Pressure	0.5 MPa to 5 MPa	At maximum flow
Gas properties	Gas chromatograph, molar mass meter	GERG-2008 equation of state [3-4]
Uncertainty (k = 2)	0.12 %	Flow ranges from 10 m^3/h to 170 m^3/h

and then switch back the diverter and measure the temperatures in inventory volume 1 and 2. Stop the registration of the outputs of the CFVN. Shortly after the tank valve is fully closed, measure the pressure in inventory volume 2; because the tank isolation valve is open at this time, the pressure in inventory 2 is equal to the pressure in the collection tank. The stop time is obtained as described above.

7) Close the tank isolation valve and vent the gas from inventory volume 2. Thereafter, isolate the collection tank from the piping using the isolation system. Wait for the scale indication to stabilize, and then measure the final mass of gas in the tank.

2.2 Model of measurement

With an overlap flow diverter (see subsection 2.1: step 5), non-negligible lost mass and/or extra mass can occur during the diversions if the diverter operating time is not very short. In the initial diversion in which the bypass line pressure under a high flow rate is higher than the initial collection-tank pressure (atmospheric for this standard system), then when both diverter valves are partially opened, extra flow can enter the control volume from the bypass valve (see Figure 1). In the final diversion in which the final tank pressure is usually much higher than that of the bypass line, extra flow can escape from the control volume. Hence, a mathematical model of the mass flow using this standard system with an overlap diverter can be proposed as Equation (1). All terms in the first line of Equation (1) represent the general formula for the time-averaged mass flow calculation. The two terms in the second line of Equation (1) arise from the overlap of the diverter valves during the diversions. The first term represents extra inflow occurring during the initial diversion, and the second term, of which the final tank pressure ($p_{tk,2}$) is expressed in the form of the CFVN flow ($q_{m,cfvn}$) multiplied by the collection time (t), represents extra outflow occurring during the final diversion. Here, it can be seen that the second term has three distinctive characteristics from the form of its formula: first, the term is almost independent of the collection time and the flow rate through a CFVN; second, the fraction of the term in Equation (1) is almost constant if the final tank pressure-ratio ($p_{by,2}/p_{tk,2}$) is small enough (for instance, not more than 0.3); third, for the previous two reasons, the term does not vanish through the process of determining the optimal trigger point of a diverter. Therefore, the term becomes a nearly constant normalized bias (systematic error) of this standard system.

In order to evaluate the effects from the overlap diverter somewhat quantitatively, especially for the amount of the extra outflow (i.e., bias), a test was performed. In this test, a CFVN (40 m^3/h) of 7.724 mm in throat diameter was used, and the collection time was fixed at 180 s. The error of the discharge coefficient (marked by

$$\overline{q_{m,cfvn}} = \frac{1}{t}\left[m + V_{inv\,1}\left(\rho_{inv\,2,2} - \rho_{inv\,1,1}\right) + V_{inv\,2}\left(\rho_{inv\,2,2} - \rho_{inv\,2,1}\right)\right] + C_{buoy}$$

$$+ \frac{1}{t} C_s\, p_{by,1}\sqrt{1-\left(\frac{p_{tk,1}}{p_{by,1}}\right)^2}\,\Delta t_{div,1} - \frac{1}{t}\, C_e C\, q_{m,cfvn}\cdot(t+t_{atm})\sqrt{1-\left(\frac{p_{by,2}}{C\, q_{m,cfvn}\cdot(t+t_{atm})}\right)^2}\,\Delta t_{div,2} \qquad (1)$$

$\overline{q_{m,cfvn}}$	*Time-averaged mass flow through a critical flow Venturi nozzle during a collection time*
$q_{m,cfvn}$	*Instant mass flow through a critical flow Venturi nozzle,* $q_{m,cfvn} \fallingdotseq \overline{q_{m,cfvn}}$
t	*Collection time*
m	*Mass of gas collected in the collection tank during a collection time*
$V_{inv\,1}$	*Inventory volume 1(see Figure 1)*
$V_{inv\,2}$	*Inventory volume 2(see Figure 1)*
$\rho_{inv\,1}$	*Gas density of inventory volume 1*
ρ_{inv2}	*Gas density of inventory volume 2*
C_{buoy}	*Buoyancy correction*
C	*Pressure coefficient*
C_s, C_e	*Flow coefficients*
p_{by}	*Gas pressure of bypass line*
p_{tk}	*Gas pressure of collection tank, the initial pressure is atmospheric*
t_{atm}	*Time required to raise the pressure of collection tank from vacuum to atmospheric pressure with a flow rate,* $q_{m,cfvn}$ *; for this standard, initial pressure of collection tank is atmospheric*
Δt_{div}	*Diverter operation time*

Subscripts

1, 2	*Numbers 1 and 2 after a comma refer to initial and final values, respectively*

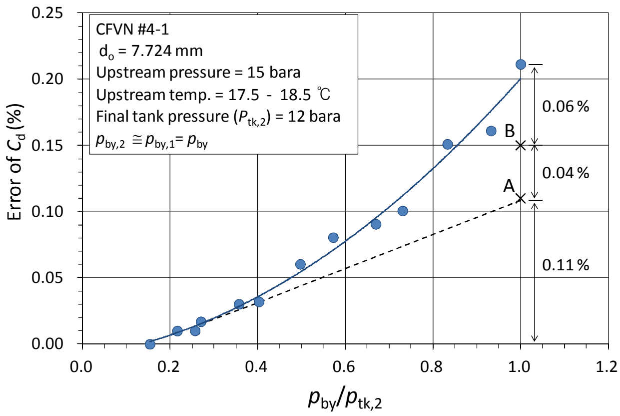

Figure 2: Effects of the overlap diverter.

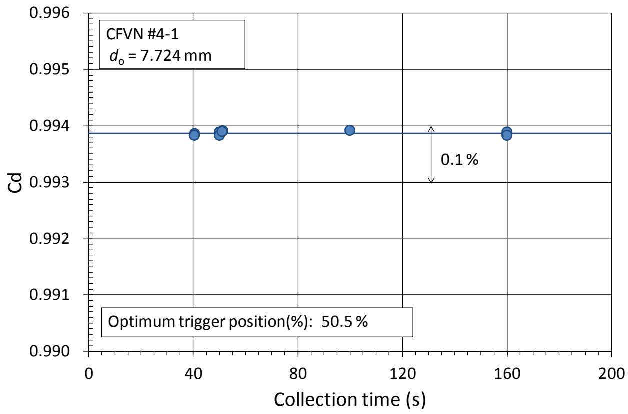

Figure 3: C_d values at an optimal trigger point.

C_d hereafter) for the CFVN was measured by increasing the bypass line pressure (or the LP storage tank pressure) from 0.18 MPa up to the final tank pressure under the initial and final tank pressures fixed at atmospheric pressure and 1.2 MPa, respectively. The final pressures in inventory volume 1 and 2, as in a regular calibration process, took the final tank pressure, which yields the effect of reducing the gas mass escaping from the control volume during the final diversion.

Figure 2 shows the test results, which indicates that, due to the overlap diverter, the error quadratically increases with the increase in pressure ratio ($p_{by}/p_{tk,2}$). However, because the error is a result of a combination of influence quantities (i.e., during the diversions, the extra CVFN-flow captured in the control volume, the extra inflow, and the extra outflow), it is necessary to separate the error in terms of each of the influence quantities. To achieve this goal, a best fitting curve of the error data is first obtained. Then, when the tangent line is drawn at the pressure ratio of 0.25, around which the error contributions of the extra outflow and the captured CFVN-flow are almost the same as those at the reference pressure ratio of 0.15, the error contribution of the extra inflow, 0.11 %, at the pressure ratio of 1.0 is obtained (marked A in Figure 2); the extra inflow term in Equation (1) is almost linear at the pressure ratio above 0.25. Considering that the error contribution of the extra captured-CFVN flow at the pressure ratio of 1.0 is about 0.04 % [5] (marked B in Figure 2), the error contribution of the extra outflow becomes about 0.06 %. Therefore, unlike in this test, in a regular calibration where the final tank pressure-ratio ($p_{by,2}/p_{tk,2}$) is less than 0.3, it can be seen that the error contribution of the extra outflow is almost constant at 0.06 % regardless of the CFVN flow and the collection time. From the view point of the piping structure, it is plausible that the error contributions of the extra inflow and outflow are almost the same under the pressure ratio of 1.0. However, because the final pressures in inventory volume 1 and 2 take the final tank pressure, the error contribution of the extra outflow becomes less than that of the extra inflow, as explained above. Here, one thing to keep in mind is that if the C_d is measured from at the pressure ratio of 0.084, meaning that p_{by} is atmospheric, then the error contribution of the extra inflow will be greater than 0.11 %.

2.3 Determination of optimal trigger point and uncertainty

The motion of the diverter (pinion-rack type) is detected with an optical sensor that generates start and stop trigger signals for timer. Because the diverter operation time of this standard system is considerably long (~90 ms), the optical sensor position (hereafter, the 'trigger point') must be accurately determined in order to minimize the timing error of the diverter. For this determination, a reference CFVN (40 m^3/h) of 7.724 mm in throat diameter is used and the test is carried out at 5 MPa, with the bypass line pressure (or the LP tank pressure) fixed at 0.25 MPa. An optimal trigger point, at which the C_d has one value regardless of the collection time, is found using the trial and error method, and the

Table 2: Uncertainty contribution.

Uncertainty category	Uncertainty (k =1)	
	Root-sum-squared term	Add term
Weigh scale readout	0.010 %	
Weigh scale calibration	0.008 %	
Timing of diverter - optimal trigger point - overlap diverter	0.007 %	0.015 %
Stability of optical sensor of timer system (background noise effect)	0.014 %	
Gas pressure	0.021 %	
Gas temperature	0.018 %	
Total effects from gas composition	0.013 %	
Critical flow function	0.024 %	
Mass of inventory	0.005 %	
Repeatability	0.010 %	
Gas leakage	0.010 %	
Combined standard uncertainty	0.061 %	
Extended uncertainty (k = 2)	0.12 %	

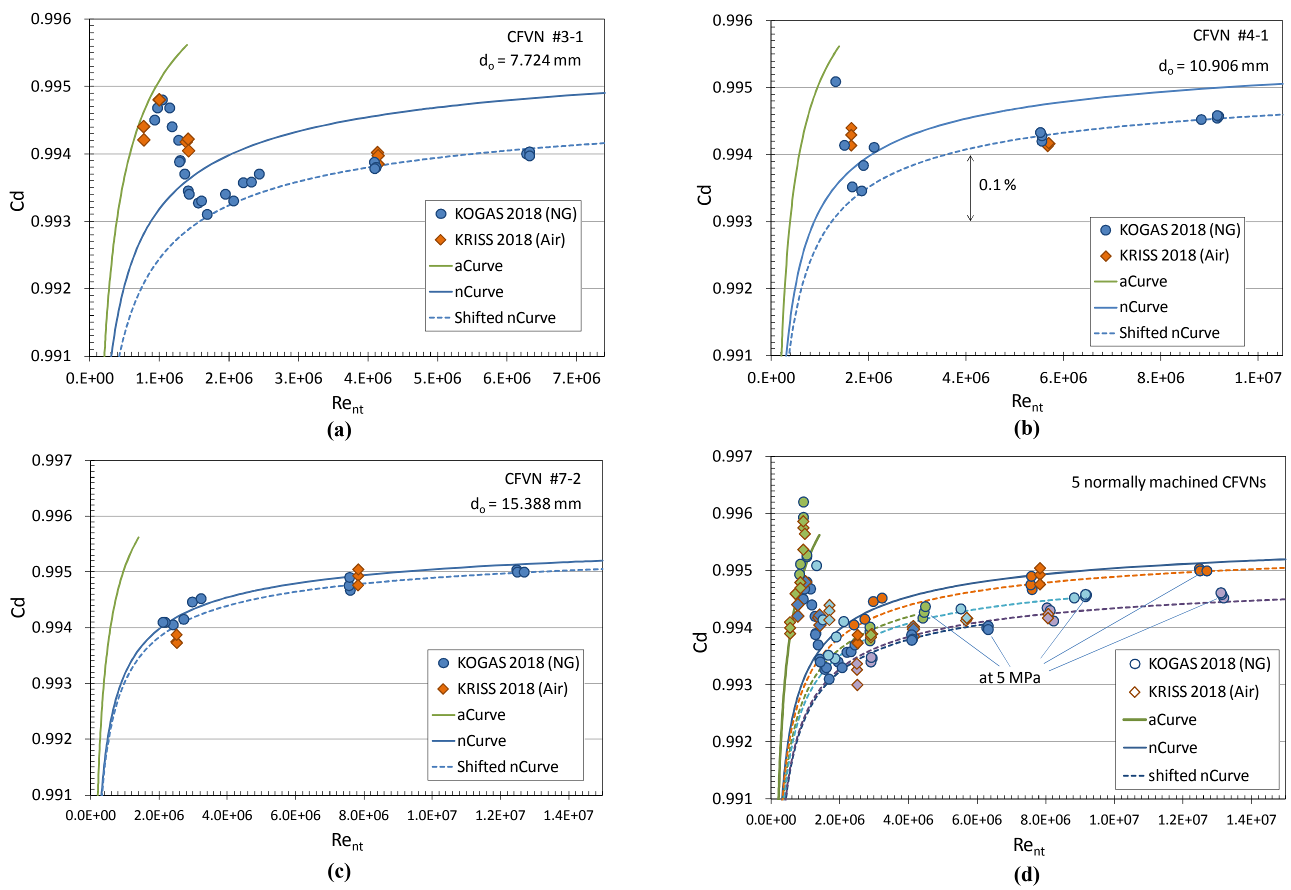

Figure 4: Inter-laboratory comparison results.

result is given in Figure 3. The result shows that C_d values are constant down to 40 s, which is the minimum collection time of the standard system. This implies three things: first, the extra inflow term— that is, the first term in the second line of Equation (1)—is vanished in the process of determining the optimal trigger point; second, the error due to the extra outflow (a bias of this standard system) is not detected in the process; third, for the previous two reasons, a standard system with an overlap diverter also has a conversed C_d value in the process.

When the trigger point is determined to have a constant C_d value of down to 40 s, the uncertainty contribution of the diverter timing is about 0.014 % (k =2). The error of extra outflow, which is a kind of diverter timing error [6], was corrected to only 0.03 %, but the remaining error of 0.03 % was left without correction. This is because, when the flow through a CFVN is much larger than 40 m^3/h (i.e., the flow used to optimize the trigger point), some error appears due to the extra inflow, and the remaining error serves to offset this error. However, to avoid underestimating the uncertainty of this standard system, the remaining error of 0.03 % was taken as an uncertainty that adds to the combined standard uncertainty. The uncertainty of this standard system is summarized in Table 2.

3. The inter-laboratory comparison result

In 2018, an inter-laboratory comparison between KOGAS and KRISS was carried out using five toroidal-throat CFVNs. The goal of the comparison was to prove the equivalence of the primary flow standards of KOGAS and KRISS using pressurized air (KRISS) and NG (KOGAS) at pressures of 0.9 MPa (≒ 1 MPa) and 3 MPa. The maximum pressure of the KOGAS primary NG-flow standard is 5 MPa, but the upper pressure was limited to 3 MPa because the maximum pressure of the KRISS primary air-flow standard is 4 MPa (which is 3 MPa in terms of NG Reynolds number under choked flow conditions). The number of measurements for each CFVN was limited to three for each pressure, except for the boundary layer transition region (i.e., the flow-transition region in CFVN throat from the laminar to turbulent boundary layer [7]). The reason for this was that, at that time, all CFVNs used as the secondary standard of the KOGAS HP calibration facility had to be calibrated at a pressure of 5 MPa, so it was necessary to minimize the period required for the comparison.

The evaluation of the data utilized the discharge coefficient C_d of the CFVNs as a function of the Reynolds number and the results are summarized in Figure 4, along with the C_d values of KOGAS, which were measured at a pressure of 5 MPa. The results show that the C_d values of KOGAS are 0.04 % to 0.05 % smaller than those of KRISS in the boundary transition region, and 0.02 % to 0.04 % larger in the non-transition region when the measurement point is at an NG pressure of near 1 MPa. When the measurement point is at an NG pressure of 3 MPa, the deviations of the C_d values between KOGAS and KRISS are within 0.03 % for all five CFVNs. At an NG pressure of 5 MPa, in which there are no C_d values of KRISS, it can be seen that the C_d values of KOGAS for each CFVN are located very close to a shifted nCurve (where 'nCurve' denotes ISO's C_d curve for the normally machined CFVN [2]), passing through the center of the KOGAS C_ds at 3 MPa of the CFVN. Since the CMCs (k=2) of KOGAS and KRISS are 0.12 % ($U_{cmc,KOGAS}$) and 0.18 % ($U_{cmc,KRISS}$), respectively, the degrees of equivalence (E_N) between KOGAS and KRISS at pressures of 1 MPa and 3 MPa using Equation (2) are within ±0.23 and ±0.14, respectively.

$$E_{N,KOGAS,KRISS} = \frac{C_{d,KOGAS} - C_{d,KRISS}}{\sqrt{U^2_{CMC,KOGAS} + U^2_{CMC,KRISS}}} \quad (2)$$

4. Conclusion

To prove the accuracy of the new static gravimetric primary standard facility at KOGAS, the systematic error, which occurred due to an overlap diverter and has not yet been identified, was estimated for this facility, and an inter-laboratory comparison between KOGAS and KRISS was performed using five CFVNs in 2018. The systematic error due to the overlap diverter of this standard system was estimated to be about 0.06 %. The degrees of equivalence between KOGAS and KRISS at pressures of 1 MPa and 3 MPa were evaluated to be within ±0.23 and ±0.14, respectively, which indicates that the measurement deviations between the two laboratories are very small. Although a comparison at a pressure of 5 MPa was not possible, the comparison results at pressures of 1 MPa and 3 MPa can cover the measurement results at 5 MPa because the calibration method and procedure for CFVNs at both pressures are identical to those at 5 MPa.

This primary standard facility is now used to calibrate the secondary standard of the KOGAS HP calibration facility and is expected to become the national standard in the near future for the HP gas flow that KRISS can not cover.

References

[1] Ha, Y. C., Park, K. A., "Design of a large-capacity flow calibration/test facility for natural gas flow-meter," *Proceedings of the 16th Int. Flow Measurement Conference FLOMEKO 2013*, Paris, 2013.

[2] ISO 9300: *Measurement of gas flow by means of critical flow Venturi nozzles,* 2005.

[3] Kunz, O., Klimeck, R., Wagner, W., Jaeschke, M., *The GERG-2004: Wide-Range Equation of State for Natural Gases and Other Mixtures*, GERG Technical Monograph 15, GERG, 2007.

[4] ISO 20765-2: Natural Gas — Calculation of thermodynamic properties — Part 2: Single-phase properties (Gas, liquid and dense fluid) for extended ranges of application, 2015.

[5] Ha, Y. C. et al., *A study on the construction and opertion of the KOGAS flow calibration /test facility for natural gas flow-meter*, Project No. RD 2012-0070, Korea Gas Corporation, Korea, 2018.

[6] Cordova, L., Lederer, T., "A practical method to assess the performance of gravimetric flow test rigs by using the timing error," *Flow Measurement and Instrumentation*, **44**, pp. 61-70, 2015.

[7] Ishibashi, M., "Discharge coefficient equation for critical-flow toroidal-throat Venturi nozzles covering the boundary-layer transition regime," *Flow Measurement and Instrumentation*, **44**, pp. 107-121, 2015.