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WET STEAM FLOWRATE CALIBRATION FACILITY

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ABSTRACT

Newly developed wet steam flowrate calibration facility is introduced. It has a closed loop in which boilers generate a steam flow up to 800 kg/h. Steam flow of known wetness up to 12 % is generated by cooling down a dry steam flow by a heat exchanger. The wetness is calculated from the enthalpy the heat exchanger draws from the dry steam flow. Analysis of the facility performance, calibration results of an orifice flowmeter calibration, and uncertainty analysis are described.

INTRODUCTION

Steam flow is widely used in industries and distinct/house heating systems since it is a very flexible medium with high heating capacity. To reduce the energy consumption in the steam systems, it is inevitable to measure the steam flowrate. However, it is often very difficult to make accurate measurements because of the wetness, i.e., water is flowing together with the vapor in the flow.

Recently, wet gas flowrate measurements were intensively investigated [1, 2, 3, 4] and an international standard on them is expected to be published in the near future. However, because its main target is mining, it is rather not suitable very much for wet steam flow metering in industries and heating systems that have relatively small wetness as well as a rigid correlation between the phases. In 1990's, Hussein [5, 6] intensively carried out researches on wet steam flowrate measurement that uses water injection into dry steam flow to generate wet steam flow of known wetness. Since the results are directly affected by the wetness, it is worth confirming the results by a facility based on a different principle to control the wetness. On the other hand, attentions were not so well paid on uncertainty and traceability in 1990's, therefore, there is another reason to , it is also worth repeat the measurements using instruments all traceable to the national standards accompanied by well defined uncertainties.

The paper introduces a new facility developed to calibrate wet steam flowmeters. It has a closed loop in which dry or wet steam flow up to 800 kg/h can be generated at a pressure up to 1.6 MPa. The saturated steam generated by two boilers in the loop is super-heated by a heater, then a cooling system controls the wetness, which is calculated from the enthalpy drawn from the superheated steam using the temperature difference and water flowrate in the cooling system. After passing the calibration line, the wet steam is totally cooled down into the water phase then the water flowrate is measured by a Coriolis flowmeter kept at the ambient temperature. All the dominating measuring instruments were calibrated and traceable to the national standards. Uncertainty analyses of typical measurements in the facility are also described in the paper.

NOMENCLATURE

Δh	enthalpy drawn from the dry steam by the heat exchanger
ρ_{water}	density of water
ρ_{steam}	density of steam
C_p	specific heat of water
Q_{cool}	water flowrate (kg/s) in the heat exchanger

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ΔT_{cool} temperature drop across the heat exchanger
x dryness (=1-wetness), mass ratio (steam/total)
h_{up} enthalpy of dry steam incoming into the heat exchanger
$Q_{orifice}$ flowrate measured by the orifice flowmeter supposing the flow is totally in the gaseous single phase using the discharge coefficient
$Q_{Coriolis}$ flowrate measured by the Coriolis flowmeter using the K-factor
f frequency of the pulses output from a flowmeter
Re the Reynolds number $\frac{4Q_{orifice}}{\pi D \mu}$ where $Q_{orifice}$ is in kg/s.
β contraction ratio of the orifice flowmeter
ΔP differential pressure across the orifice flowmeter
A orifice area
$K_{f\,(Coriolis)}$ K-factor of the Coriolis flowmeter (P/m^3)

THE WET STEAM CALIBRATION FACILITY

The block diagram of the wet steam calibration facility and a picture of its measuring area are shown in Figs. 1 and 2.

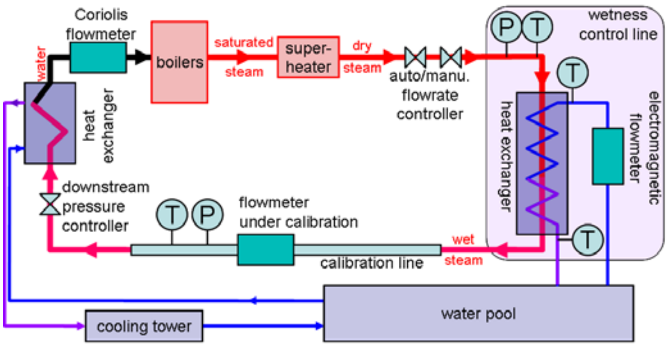

FIGURE 1. THE WET STEAM CALIBRATION FACILITY

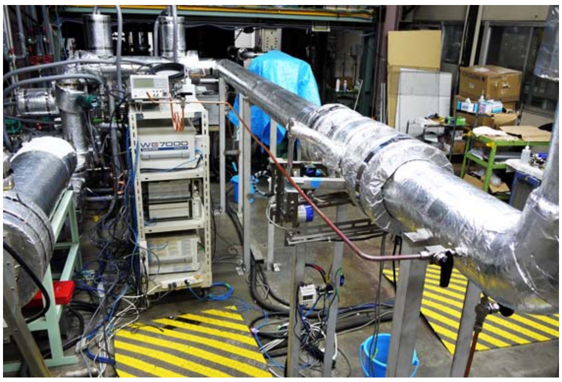

FIGURE 2. THE MEASURING AREA OF THE FACILITY; THE CALIBRATION LINE (RIHGT), THE WETNESS CONTROL LINE (FAR SIDE), AND THE SUPER-HEATER (LEFT)

The facility has a closed loop, in which two boilers generate a saturated steam flow up to 800 kg/h at a pressure up to 1.6 MPa. The steam from the boilers is dried by a super-heater at the upstream of the wetness control line. The flowrate of the dried steam is controlled by the automatic and manual flowrate controllers.

In the wetness control line, the dried steam is cooled down by a heat exchanger, in which cold water is flowing. The flowrate of the water is measured by an electromagnetic flowmeter (YOKOGAWA) that was calibrated directly by the national standard for small water flowrate in Japan at AIST [7] (Fig. 3) by water at room temperature at flowrates from 0.05 m^3/h to 1 m^3/h. The calibration was carried out using the weighing system and the uncertainty is smaller than 0.04 % (k=2). The pulses output from the flowmeter (typically 100 ~ 500 Hz) are accumulated for several ten thousands periods through A/D converter then the stability of the pulse frequency is analyzed based on the pulse waveform in a PC. It evaluates the frequency each time when the transition is detected as shown in Fig. 4, therefore, there is no error caused by incorporating a portion of period when calculating the averaged frequency. It also enables to estimate how the frequency gets stable along with the accumulation that can reveal, e.g., pulsating flow, malfunction of flowmeter, stability of facility and so on. Based on the analysis of pulse waveform, an averaged frequency is calculated in an adequate accumulating period. The typical period to average the pulses is 3 ~ 5 minutes.

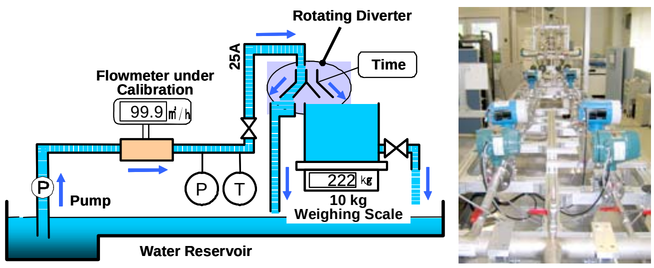

FIGURE 3. THE WATER FLOW CALIBRATION FACILITY AT AIST (THE NATIONAL STANDARD FOR SMALL WATER FLOW IN JAPAN) EMPLOYED TO CALIBRATE THE ELECTROMAGNETIC FLOWMETER IN THE WETNESS CONTROL LINE. THE CORIOLIS FLOWMETER WAS ALSO CALIBRATED IN THE FACILITY.

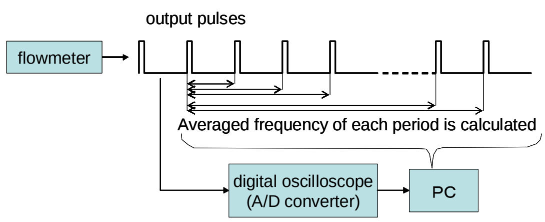

FIGURE 4. FREQUENCY MEASUREMENT PRINCIPLE

The wetness control line measures the water temperatures at the inlet and outlet of the heat exchanger by 4-wired PT100

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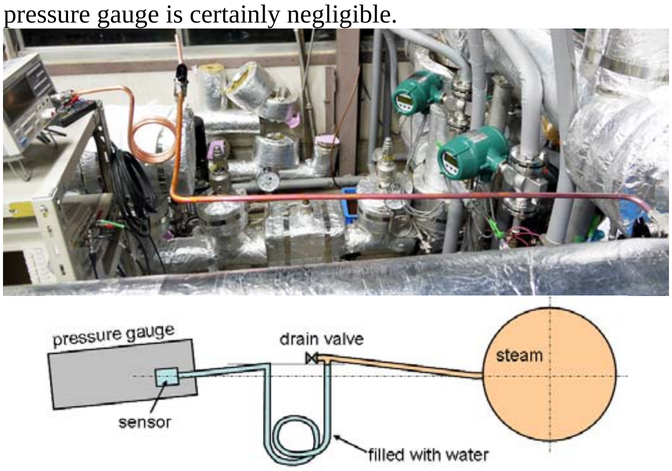
sensors and a digital multimeter (Keithley 2001 with a scanner board). The temperature sensors were calibrated in the scheme of JCSS (Japan Calibration Service System), that is, they were calibrated by an accredited calibration laboratory traceable to the national standards in Japan. All the uncertainties of the PT100 temperature sensors employed in the facility are smaller than 0.03 % (k=2).

The pressure and temperature of the dried steam flowing into the wetness control line are measured by a digital pressure gauge (YOKOGAWA MT220) and a PT100 temperature in the same way as in the wetness control line, respectively. The pressure gauge was calibrated also by JCSS at an uncertainty smaller than 0.03 % (k=2). As shown in Fig. 5, the pressure line from the steam line is partly filled with water to protect the pressure gauge from overheat. The water head applied on the sensor is kept constant regardless of the condensation of the steam. The head height is intermittently monitored through the drain valve. Since 1 mmH_2O is about 10 Pa and the minimum pressure in the calibrations is about 300 kPa, 1 cm difference of the head, for example, will result in only 0.003 % difference, therefore, the uncertainty caused by the variation of head on the pressure gauge is certainly negligible.



FIGURES 5. PRESSURE LINE

In the calibration line where the flowmeter under calibration is installed, temperatures and pressures are measured in the adequate manner depending on the flowmeter. The pressure gauge and temperature measuring system for the calibration line are as the same ones as explained above.

At the downstream of the calibration line, the wet steam is cooled down by a heat exchanger and put whole in the water phase afterward. The total flow through the calibration line is measured as the flowrate of the fully cooled down water, which is measured by a Coriolis flowmeter that is kept at the atmospheric temperature. The Coriolis flowmeter was also calibrated in the same way and the same range as the electromagnetic flowmeter at the uncertainty of 0.04 % (k=2). The frequency of the pulses output from the Coriolis flowmeter (typically 50 ~ 200 Hz) is measured in the same way as for the electromagnetic flowmeter.

The measuring system is summarized in Fig. 6. An independent monitor system using a logger with its own sensors is also employed, thus almost all the measurements are duplicated and checked by each other if necessary. Pressures and temperatures are averaged in the period where the pulses from the flowmeters are being accumulated.

Using the flowrate of the cooling water in the wetness control line and its temperature drop through the heat exchanger, the enthalpy drawn from the steam in the main line is given by

$$\Delta h = \rho_{water} C_p Q_{cool} \Delta T_{cool} \tag{1}$$

where ρ and C_p are calculated using the international equation of state IAPWS-IF97 [8], then the steam quality $x(=1-\text{wetness})$ at the downstream of the wetness controlling line is calculated by using the temperature and the pressure of the steam flowing into the heat exchanger

$$x = 1 - \frac{h_{up} - \Delta h - h_l}{h_g - h_l} \tag{2}$$

where h_{up}, h_g, and h_l are the enthalpies of the incoming steam, the saturated vapor at the inlet condition, and the saturated water at the inlet condition of the wetness control line, respectively. The facility currently can generate a wetness up to 12 % and it will be doubled in the near future.

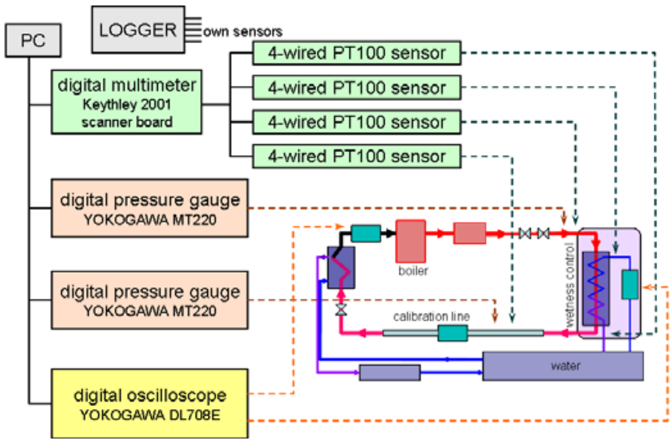


FIGURE 6. MEASURING SYSTEM

COMPARISON OF THE CALIBRATION RESULTS OF AN ORIFICE FLOWMETER BY DRY AIR AND DRY STEAM

An orifice flowmeter was calibrated by both dry air and dry steam (super-heated steam) at the same Reynolds number range to confirm the consistency of the facilities for steam, water, and air. The orifice plate is a kind of corner tap but it does have a unique shape as shown in Fig. 7, that is, it has a quadrant inlet contraction with its edge facing to the downstream.

A calibration using the dry air at the atmospheric temperature was carried out by the national standard facility in

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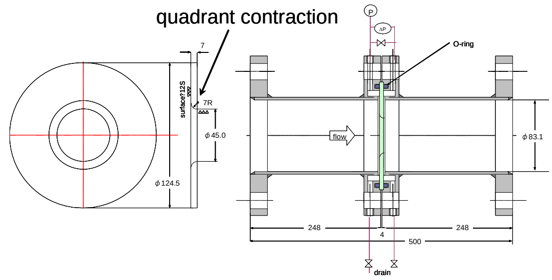
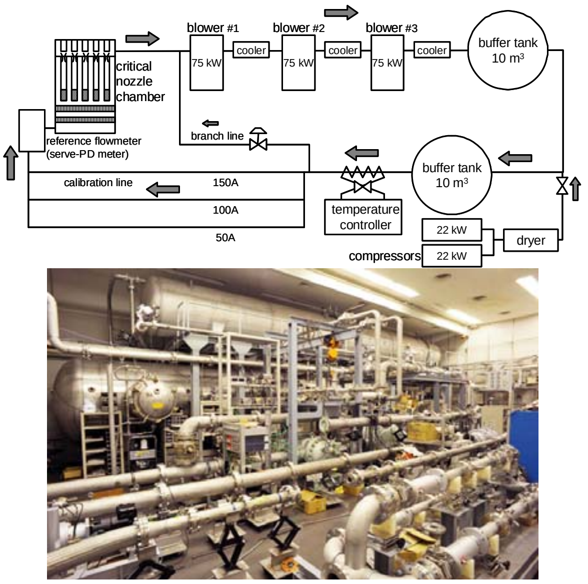
Japan for the middle air flowrate at AIST shown in Fig. 8 [9]. It has a closed loop to perform pressurized calibrations. Three blowers connected in series generate a flow up to 1000 m^3/h at a pressure up to 1 MPa. The reference of the facility is a parallel connection of critical flow Venturi nozzles machined by a super-accurate lathe that were calibrated by a constant volume tank system developed as the national standard in Japan.



FIGURES 7. THE ORIFICE FLOWMETER UNDER CALIBRAION



FIGURES 8. THE AIR FLOW FACILITY AT AIST EMPLOYED TO CALIBRATE THE ORIFICE FLOWMETER; THE LOWER TANK ON THE FAR SIDE IS THE CONSTANT VOLUME TANK AS THE NATIONAL STANDARD IN JAPAN

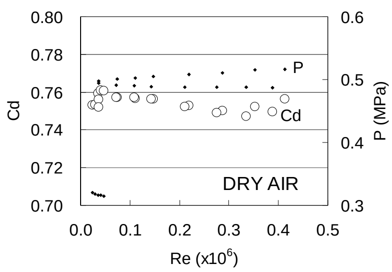


FIGURE 9. THE CALIBRATION RESULT OF THE ORIFICE FLOWMETER BY DRY AIR

To have the same Reynolds number range as in the steam calibration, the orifice flowmeter was calibrated by air at 0.3 MPa from 25 to 50 m^3/h and also at 0.5 MPa from 25 to 300 m^3/h that resulted in the Reynolds numbers from 2.3×10^4 to 4.1×10^5. As shown in Fig. 9, the discharge coefficient is almost constant within ±0.5 % over the Reynolds number range

The orifice flowmeter was also calibrated in the wet steam calibration facility against the Coriolis flowmeter, that is, the flowrate indications of the orifice and the Coriolis flowmeters, $Q_{orifice}$ and $Q_{Coriolis}$, respectively, were compared. The flowrate indication of the orifice flowmeter includes the discharge coefficient shown in Fig. 9 at the same Reynolds number.

$$Q_{orifice} = \frac{C_d\left(Re_{steam}\right)}{\sqrt{1-\beta^4}} A\sqrt{2\Delta P \rho_{steam}} \quad \text{(kg/s)} \qquad (3)$$

The flowrate indication by the Coriolis flowmeter was also corrected by the K-factors measured at the calibration at AIST.

$$Q_{Coriolis} = \rho_{water} K_{f(Coriolis)} f \quad \text{(kg/s)} \qquad (4)$$

The flowrate indications, Eqs. (3) and (4), should have the same value in case of dry steam flow if all the facilities are consistent with each other. The discrepancies of these values are shown in Fig. 10 where the void points are raw data and the solid points are their averages. There is a dependence of the discrepancy on the flow velocity observed, reason of which is unknown at this moment. The stagnation correction is in the order of 0.05 % at the largest, thus it will not cause such a large deviation. Since the scatterings and deviations at the both extremes of the flow velocity range (red points) are considerably large, measurements at these flow velocities were abandoned, then all the discrepancies are within±1 %, which is good enough for steam flowrate measurements. The small dependence on the flow velocity is left as it is in the further measurements.

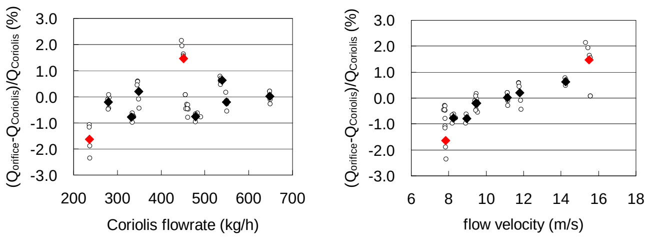


FIGURE 10. DISCREPANCIES OF THE INDICATIONS OF THE ORIFICE AND CORIOLIS FLOWMETERS IN THE WET STEAM FLOWRATE CALIBRATION FACILITY FLOWING DRY STEAM; SOLID POINTS ARE AVERAGED VALUES

SYNCHRONY OF THE STEAM AND WATER FLOW

The phase change from the steam to water may cause a non-synchrony or in the worst case no-correlation in their

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flowrates at the water line and at the calibration line because of the quite large change of the volume between the phases. It is confirmed that this is not the case in the facility as shown in Fig. 11. The facility was operated without operating its automatic flowrate controller that resulted in the steam flowrate variation following the automatic turn on and off of the boilers. The variation of the differential pressure across the orifice flowmeter exactly followed the variation of the water flowrate as shown in the figure, therefore it is concluded that the water flow measured by the Coriolis flowmeter synchronously represents the total steam flow in the calibration line. When using the automatic flowrate control valve, the stability of the water flowrate is slightly improved as shown in Fig. 12.

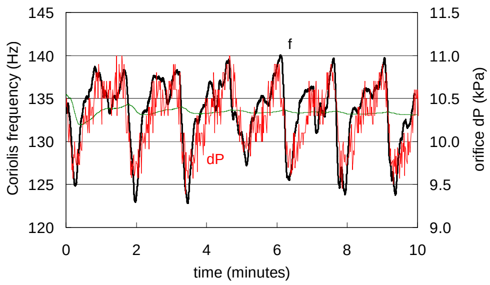

FIGURE 11. CORRELATION OF DIFFERENTIAL PRESSURE ACROSS THE ORIFICE FLOWMETER (RED LINE) AND THE WATER FLOWRATE MEASURED BY THE CORIOLIS FLOWMETER (BLACK LINE) WHEN THE FACILITY IS OPERATING WITHOUT THE AUTOMATIC FLOWRATE CONTROL; THIN LINE IS THE AVERAGED FREQUENCY OVER THE ACCUMULATED PERIOD

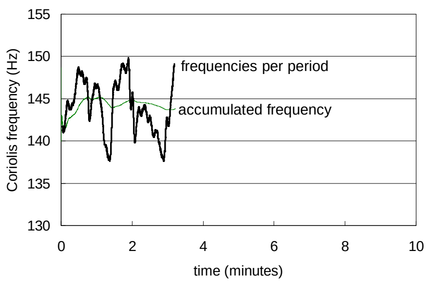

FIGURE 12. STABILITY IMPROVED BY THE AUTOMATIC FLOWRATE CONTROL VALVE

DEVIATION OF ORIFICE INDICATION FROM THE TOTAL FLOWRATE IN WET STEAM FLOW

In Fig. 13, indications of the orifice flowmeter $Q_{orifice}$ in wet steam flow were compared with the total flowrates $Q_{Coriolis}$ at various wetnesses. As expected, indication of the orifice flowmeter has a deviation from the total flowrate by almost the same amount as the wetness. This is because orifice flowmeter will not have a significant sensitivity on the existence of liquid of small amount because of the negligible volume of liquid comparing with gas. This was also confirmed by Hussein's experiments [5], which are also shown in Fig. 13 by the void points. Although Hussein did not describe the shape of his orifice plate, this good agreement implies that these results are versatile for various shapes of the orifice plates since the one employed in the present research work has very unique shape for an orifice plate.

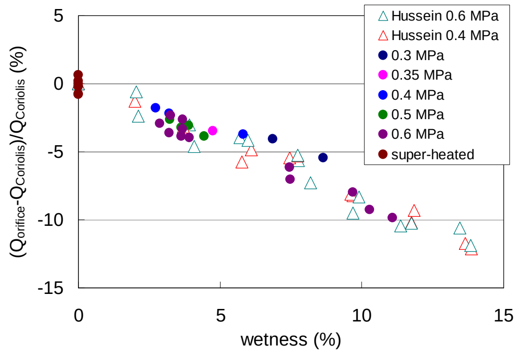

FIGURE 13. COMPARISON OF THE ORIFICE FLOWMETER INDICATIONS WITH THE TOTAL FLOWRATE MEASURED BY THE CORIOLIS FLOWMETER AT VARIOUS WETNESSES

DEVIATION OF ORIFICE INDICATION FROM THE STEAM (GASEOUS) FLOWRATE IN WET STEAM FLOW

In Fig. 14, the indication of the orifice flowmeter is compared with the steam flowrate (net flowrate of the gaseous phase) in the calibration line, which is obtained from the wetness defined at the wetness control line and the total flowrate measured by the Coriolis flowmeter. The orifice flowmeter behaves the well-known over-reading, that is, the positive error in the indication of gas flow meter in wet flow from the net gaseous flowrate [1-6]. The solid line is the linear fitting of all the points with fixing its one end at the origin. The behavior and the possibility of its correction will be discussed in the details in another paper [10].

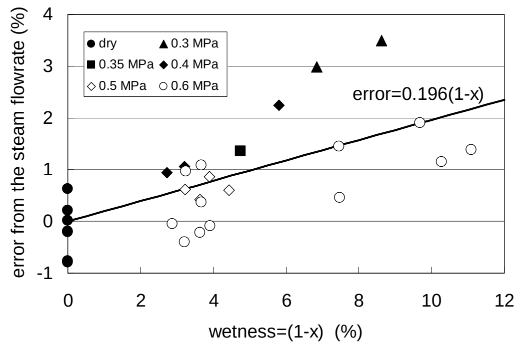

FIGURE 14. THE DEVIATION OF THE INDICATION OF THE ORIFICE FLOWMETER FROM THE NET STEAM FLOWRATE (EXCLUDING THE WATER FLOWRATE) AT THE CALIBRATION LINE

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UNCERTAINTY ANALYSIS

Uncertainty of the measurement was estimated according to GUM [11] and summarized in the followings.

The standard uncertainties of the elemental mesurands, those of intermediate quantities, those of dryness and its related quantity, and those of orifice flowmeter are listed in Tabs. 1, 2, 3, and 4, respectively. According to the analysis, the facility can measure the total and the steam (gaseous) flowrates with a combined uncertainty (*k*=2) of 0.57 % and 0.61 %, respectively.

About the measurements using the orifice flowmeter, the differential pressure gauge did not have high enough resolution that resulted in largest uncertainty in the budget, which will be improved in the future measurements. At the current situation, the combined uncertainty of the difference of the steam flowrate measured by the orifice flowmeter and that by the Coriolis flowmeter is concluded at 0.8 ~ 1.0 % (*k*=2).

TABLE 1. THE UNCERTAINTIES OF THE ELEMENTAL MEASURANDS

Measurands	A type standard uncertainy (%)	B type standard uncertainty (%)
absolute pressures	0.03	0.03 %
differential pressure	0.18	0.29 ~ 1.44
temperatures	0.04	0.03
CO frequency	0.28	0.03
EM frequency	0.18	0.03

CO= Coriolis flowmeter, EM= electromagnetic flowmeter

TABLE 2. THE UNCERTAINTIES OF THE INTERMEDIATE QUANTITIES

Quantity	A type standard uncertainy (%)	B type standard uncertainty (%)
CO flowrate	0.28	0.04
	combined 0.57 % (*k*=2)	
EM flowrate	0.18	0.09
Dryness	0.10	0.05
Steam (gaseous) flowrate	0.30	0.06
	combined 0.61 % (*k*=2)	

TABLE 3. THE UNCERTAINTIES RELATED TO THE ORIFICE FLOWMETER

Quantity	A type standard uncertainy (%)	B type standard uncertainty (%)
OF discharge coefficient	0.09	0.26 ~ 0.75
Steam flowrate difference	0.31	0.23 ~ 0.41
	combined 0.8 ~ 1.0 % (*k*=2)	

OF= orifice flowmeter

CONCLUSION

A newly developed wet steam flowrate calibration facility was introduced in the details. The facility measures the total flowrate in the calibration line by a Coriolis flowmeter after the flow is totally cooled down into water. The wetness is introduced by cooling down the dry steam, wetness of which is calculated using the enthalpy drawn from the dry steam by the heat exchanger. Some performance estimations were performed to demonstrate the proper operation of the facility. Calibration results of an orifice flowmeter using dry steam in the facility and dry air in the air flowrate standard facility in Japan agreed with each other within ±1%. Measurement results using an orifice flowmeter agreed very well with the past measurements. Uncertainty analysis showed that the facility can measure the total and the steam (gaseous) flowrates at the combined uncertainty (*k*=2) of 0.57 % and 0.61 %, respectively. The combined uncertainty of the flowrate difference between the orifice flowmeter and the Coriolis flowmeter was estimated at 0.8 ~ 1.0 % (k=2). There was well-known over-reading observed in the orifice flowmeter when wet steam was flowing in it.

ACKNOWLEDGMENTS

The authors thank to Dr. Noriyuki Furuichi who calibrated the electromagnetic and the Coriolis flowmeters.

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