INTERNATIONAL
STANDARD

ISO
18213-5

First edition
2008-03-15

Nuclear fuel technology — Tank calibration and volume determination for nuclear materials accountancy —

Part 5:
Accurate determination of liquid height in accountancy tanks equipped with dip tubes, fast bubbling rate

Technologie du combustible nucléaire — Étalonnage et détermination du volume de cuve pour la comptabilité des matières nucléaires —

Partie 5: Détermination précise de la hauteur de liquide dans une cuve bilan équipée de cannes de bullage, bullage rapide

Reference number
ISO 18213-5:2008(E)

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Foreword

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ISO 18213-5 was prepared by Technical Committee ISO/TC 85, *Nuclear energy*, Subcommittee SC 5, *Nuclear fuel technology*.

ISO 18213 consists of the following parts, under the general title *Nuclear fuel technology — Tank calibration and volume determination for nuclear materials accountancy*:

- *Part 1: Procedural overview*
- *Part 2: Data standardization for tank calibration*
- *Part 3: Statistical methods*
- *Part 4: Accurate determination of liquid height in accountancy tanks equipped with dip tubes, slow bubbling rate*
- *Part 5: Accurate determination of liquid height in accountancy tanks equipped with dip tubes, fast bubbling rate*
- *Part 6: Accurate in-tank determination of liquid density in accountancy tanks equipped with dip tubes*

Introduction

ISO 18213 deals with the acquisition, standardization, analysis, and use of calibration data to determine liquid volumes in process tanks for accountability purposes. This part of ISO 18213 is complementary to the other parts, ISO 18213-1 (procedural overview), ISO 18213-2 (data standardization), ISO 18213-3 (statistical methods), ISO 18213-4 (slow bubbling rate) and ISO 18213-6 (in-tank determination of liquid density).

The procedure presented herein for determining liquid height from measurements of induced pressure applies specifically when a fast bubbling rate is employed. A similar procedure that is appropriate for a very slow bubbling rate is given in ISO 18213-4.

Measurements of the volume and height of liquid in a process accountancy tank are often made in order to estimate or verify the tank's calibration or volume measurement equation. The calibration equation relates the response of the tank's measurement system to some independent measure of tank volume.

Beginning with an empty tank, calibration data are typically acquired by introducing a series of carefully measured quantities of some calibration liquid into the tank. The quantity of liquid added, the response of the tank's measurement system, and relevant ambient conditions such as temperature are measured for each incremental addition. Several calibration runs are made to obtain data for estimating or verifying a tank's calibration or measurement equation. A procedural overview of the tank calibration and volume measurement process is given in ISO 18213-1. An algorithm for standardizing tank calibration and volume measurement data to minimize the effects of variability in ambient conditions that prevail during the measurement period is given in ISO 18213-2. The procedure presented in this part of ISO 18213 for determining the height of calibration liquid in the tank from a measurement of the pressure it induces in the tank's measurement system is a vital component of that algorithm.

In some reprocessing plants, the volume of liquid transferred into or out of a tank is determined by the levels of two siphons. The high level corresponds to the nominal volume, and the low level to the heel volume. If the transfer volume cannot be measured directly, then it is necessary to calibrate this volume (as described in the previous paragraph) because the difference between the actual volume and that used for inventory calculations will appear as a systematic error.

The ultimate purpose of the calibration exercise is to estimate the tank’s volume measurement equation (the inverse of the calibration equation), which relates tank volume to measurement system response. Steps for using the measurement equation to determine the volume of process liquid in the tank are presented in ISO 18213-1. The procedure presented in this part of ISO 18213 for determining the height of process liquid in a tank from a measurement of the pressure it induces in the tank's measurement system is also a key step in the procedure for determining process liquid volumes.

Nuclear fuel technology — Tank calibration and volume determination for nuclear materials accountancy —

Part 5:
Accurate determination of liquid height in accountancy tanks equipped with dip tubes, fast bubbling rate

1 Scope

This part of ISO 18213 specifies a procedure for making accurate determinations of liquid height in nuclear-materials-accountancy tanks that are equipped with pneumatic systems for determining the liquid content. With such systems, gas is forced through a probe (dip tube) whose tip is submerged in the tank liquid. The pressure required to induce bubbling is measured with a manometer located at some distance from the tip of the probe. This procedure applies specifically when a fast bubbling rate is employed.

A series of liquid height determinations made with a liquid of known density is required to estimate a tank's calibration equation (see ISO 18213-1), the function that relates the elevation (height) of a point in the tank to an independent determination of tank volume associated with that point. For accountability purposes, the tank's measurement equation (the inverse of its calibration equation) is used to determine the volume of process liquid in the tank that corresponds to a given determination of liquid height.

2 Physical principles involved

The methodology in this part of ISO 18213 is based on measurements of the difference in hydrostatic pressure at the base of a column of liquid in a tank and the pressure at its surface, as measured with a bubbler probe inserted into the liquid. Specifically, the pressure, P, expressed in pascals, exerted by a column of liquid at its base is related to the height of the column and the density of the liquid, in accordance with Equation (1)[1]:

$$P = gH_\mathrm{M}\rho_\mathrm{M} \tag{1}$$

where

H_M is the height of the liquid column (at temperature T_m), in m;

ρ_M is the average density of the liquid in the column (at temperature T_m), in kg/m^3;

g is the local acceleration due to gravity, in m/s^2.

For a liquid of known density, ρ, Equation (1) can be used to determine the height, H, of the column of liquid above a given point from (a measurement of) the pressure, P, exerted by the liquid at that point. Therefore, process tanks are typically equipped with bubbler probe systems to measure pressure. Components of a typical pressure measurement system (see Figure 1) are discussed in detail in ISO 18213-1, together with a description of the procedural aspects of a typical calibration exercise.

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[1] The subscript “M” is used to indicate the value of a temperature-dependent quantity at the temperature T_m.

In practice, it is not absolute pressure that is measured, but rather the difference in pressure between the bottom and the top of the liquid column. Gas is forced through two probes to measure this differential pressure. The tip of one probe (the long or major probe) is located near the bottom of the tank and immersed in the liquid. The tip of the second probe (reference probe) is located in the tank above the liquid surface.

Various factors can affect the accuracy of the height determinations that follow from Equation (1). Temperature variations potentially have the greatest effect, especially on the comparability of two or more measurements (such as those taken for calibration), primarily because liquid density changes with temperature. Moreover, differences between actual pressures at the tip of the probes and observed pressures at the manometer can result from the buoyancy effect of air, the mass of gas in the probe lines, flow resistance, and the effects of bubble formation and release at the tip of the probes. A general algorithm for standardizing pressure measurements that compensates for temperature variations and other measurement factors is presented in ISO 18213-2. For the case in which pressure measurements are made with a fast bubbling rate, details of the pressure-to-height calculation step of this standardization algorithm are presented in Clause 4 of this part of ISO 18213. Analogous calculations that apply for a slow bubbling rate are given in ISO 18213-4. Procedures for estimating the uncertainty of the resulting height determinations are given in ISO 18213-3.

3 Required equipment, measurement conditions, and operating procedures

The pressure measurements to which this part of ISO 18213 applies are made either to calibrate a tank or to determine the volume of process liquid it contains. The same equipment, operating procedures, and standardization steps are used for both purposes. The elements of a pressure measurement system for determining the liquid content of a process tank are described in detail in Clause 4 of ISO 18213-1:2007. Measurement conditions and operating procedures for making pressure measurements to determine liquid height are described in detail in Clause 6 of ISO 18213-1:2007.

4 Determination of height from measurements of pressure

As noted in Clause 2, several factors can affect the accuracy of the calculation for determining height from pressure based on Equation (1). Adjustments that compensate for these factors are identified in this clause. See References [6] and [8].

If the effect of atmospheric pressure is taken into account, the fundamental relationship for determining liquid height from pressure is obtained from Equation (1), in accordance with Equation (2)[2]:

$$gH_{1,\mathrm{M}}\rho_{\mathrm{M}} = P_1(H) - P(H_{1,\mathrm{M}} + H) \tag{2}$$

where

g	is the local acceleration due to gravity;
ρ_{M}	is the average density of liquid in the tank;
$H_{1,\mathrm{M}}$	is the height of the column of liquid in the tank above the tip of the bubbling (major) probe;
$P_1(H)$	is the pressure at the tip of the bubbling probe (at elevation H above reference point r_1);
$P(H_{1,\mathrm{M}} + H)$	is the ambient pressure minus off-gas pressure at the liquid surface in the vapour space [at elevation $(H_{1,\mathrm{M}} + H)$ above reference point, r_1].

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[2] The subscript "1" is used in this part of ISO 18213 to indicate quantities that refer to the major probe (see Figure 1). The steps for standardizing data from a second probe are completely analogous.

It is convenient to take the bottom of the tank or the tip of the measuring (major) probe as the primary reference point. If the bottom of the tank is selected as the primary reference point, then $H = \varepsilon$ in the nomenclature of Figure 1. If the tip of the measuring probe is selected as the primary reference point, then $H = 0$. Under the latter convention, Equation (2) can be written in accordance with Equation (3):

$$gH_{1,\mathrm{M}}\rho_{\mathrm{M}} = P_1(0) - P(H_{1,\mathrm{M}}) \tag{3}$$

where

$P_1(0)$ denotes the pressure at the tip of major probe;

$P(H_{1,\mathrm{M}})$ denotes the ambient pressure minus off-gas pressure at the liquid surface.

As noted in Clause 2, it is not possible to directly measure the quantities in Equation (1), nor is it possible to directly measure the quantities in Equation (3). In practice, the difference in pressure between the major probe and the reference probe, in accordance with Equation (4), is measured by a manometer located at some elevation, E_1, above the primary reference point (see Figure 1).

$$\Delta P_1 = P_1(E_1) - P_\mathrm{r}(E_1) \tag{4}$$

However, the pressure at the tips of the major and reference probes may differ from the pressure measured at the manometer because of

- the mass of gas in the pressure lines,
- differences in the densities of gas (air) in the pressure lines and in the vapour space,
- flow resistances in the pressure lines,
- the effects of bubble formation at the tip of the major probe, and
- surface tension and pressure associated with the formation of bubbles at the tip of the major probe.

Equations (5), (6) and (7) give the basic relationships among these factors. Equation (5) gives the pressure at the tip of the major probe:

$$P_1(0) = gH_{1,\mathrm{M}}\rho_{\mathrm{M}} + g(E_1 - E_\mathrm{r} - H_{1,\mathrm{M}})\,\rho_{\mathrm{a,s}} + P_\mathrm{r}(E_1 - E_\mathrm{r}) \tag{5}$$

where

g is the local acceleration due to gravity;

ρ_M is the average density of liquid in the tank;

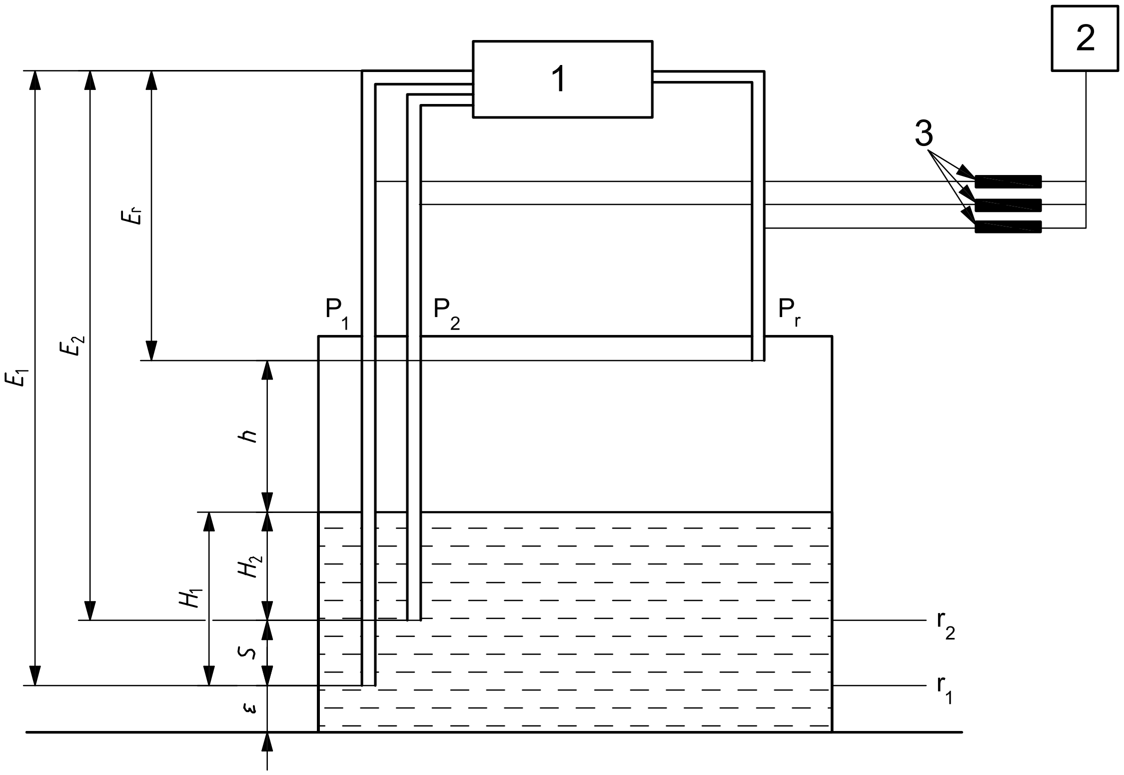
$H_{1,\mathrm{M}}$ is the height of liquid in the tank relative to the primary reference point, r_1, (the tip of the major probe);

E_1 is the elevation of the manometer above the primary reference point, r_1;

E_r is the elevation of the manometer above the tip of the reference probe;

$\rho_{\mathrm{a,s}}$ is the average density of air in the tank above the liquid surface at the prevailing pressure (atmospheric pressure minus off-gas pressure).

The first term on the right-hand side of Equation (5) represents the pressure exerted by the liquid in the tank above the tip of the major probe; the second term represents the pressure exerted by the air in the tank between the surface of the liquid and the tip of the reference probe; and the last term represents the pressure at the tip of the reference probe.



NOTE This configuration is typical but other configurations are possible; see Reference [11] for examples.

Key

1 manometer

2 gas supply (N_2 or air)

3 flowmeters

Probe	Major probe	Minor probe	Reference probe
Probe designation	P_1	P_2	P_r
Reference point	r_1 (primary)	r_2 (secondary)	—
Height of liquid above reference point	H_1	H_2	—
Elevation of pressure gauge (manometer) above reference point	E_1	E_2	E_r
Elevation of reference probe above liquid surface	$h = E_1 - E_r - H_1$	$h = E_2 - E_r - H_2$	—
Elevation of reference point above bottom of tank	ε	$\varepsilon + S$ [a]	—

[a] Vertical distance (probe separation): $S = H_1 - H_2$.

Figure 1 — Elements of a typical pressure measurement system for determining liquid content

Equation (6) gives the pressure at the manometer in the major probe line:

$$P_1(E_1) = P_1(0) + \delta_1 - gE_1\rho_{g,1} + g\lambda(\rho_M - \rho_{g,1}) + 2\sigma/r_b \tag{6}$$

where

δ_1 is the pressure drop in the major probe line due to the gas flow resistance;

$\rho_{g,1}$ is the average density of gas in the major probe line at the prevailing pressure;

λ is the distance of the lowest point of the bubble below the tip of the major probe;

σ is the surface tension for the liquid and gas;

r_b is the radius of curvature of the bubble at its lowest point.

The first term on the right-hand side of Equation (6) represents the pressure at the tip of the major probe; the second term represents the pressure drop in the major probe line due to flow resistance; the third represents pressure exerted by the gas in the major probe line; the fourth term gives the pressure of a column of liquid equal in height to the average distance of the lowest point of the bubble below the tip of the major probe; and the last term accounts for the surface tension at the interface between the tank liquid and the gas in the major probe line.

Finally, Equation (7) gives the pressure, at the manometer, in the reference probe line:

$$P_r(E_1) = P_r(E_1 - E_r) + \delta_r - gE_r\rho_{g,r} \tag{7}$$

where

$\rho_{g,r}$ is the average density of gas in the reference probe line at the prevailing pressure;

δ_r is the pressure drop in the reference probe line due to gas flow resistance.

The first term on the right-hand side of Equation (7) represents the pressure at the tip of the reference probe; the next term represents the pressure drop in the reference probe line due to flow resistance; and the last term represents the pressure exerted by the gas in the reference probe.

If the expression for $P_1(0)$ given by Equation (5) is first substituted into Equation (6), and then Equation (7) is subtracted from Equation (6), the following expression is obtained for the liquid height $H_{1,M}$:

$$H_{1,M} = [\Delta P_1 + gE_1(\rho_{g,1} - \rho_{a,s}) - gE_r(\rho_{g,r} - \rho_{a,s}) + (\delta_r - \delta_1) - g\lambda(\rho_M - \rho_{g,1}) - 2\sigma/r_b]/[g(\rho_M - \rho_{a,s})] \tag{8}$$

The expression in Equation (8) for determining $H_{1,M}$ from the measured differential pressure, ΔP_1, includes adjustments that compensate for all the factors identified in this clause. The expression is valid at the measurement temperature, T_m.

The accuracy of height determinations obtained by means of Equation (8) is limited by how well the density of the measured liquid is determined at the prevailing temperature. It is also important to note that $H_{1,M}$ is the height of the liquid in the tank only at the measurement temperature, T_m. In particular, $H_{1,M}$ is not the height of the same liquid at some other temperature.

Some of the effects identified in Equation (8) may be quite small. Whether or not they must be taken into account depends on the capability of the tank's measurement system (e.g. manometer) and required measurement accuracy. An algorithm for estimating the quantities in Equation (8) is given in Annex A. In general, these quantities should be measured whenever possible. However, under normal operating conditions, use of the suggested default values instead of actual measurements will provide acceptable results in nearly all situations.

5 Results

Starting with a measure of the pressure required to induce bubbling at the tip of a probe submerged in the liquid in an accountancy tank, the standardization procedure described in Clause 4 yields an accurate measure of the height of the column of liquid exerting the pressure. With high-precision manometers and good technique applied under stable conditions, it is possible to achieve relative accuracies for individual height determinations in the range of 0,01 to 0,02 %[3), 4)] for pressures of approximately 10 000 Pa or greater. This degree of accuracy corresponds to 1 Pa to 2 Pa, or approximately 0,1 mm to 0,2 mm for a 1 m column of water.

The accuracy of liquid height determinations obtained from Equation (8) is limited by the accuracy of available measurements of liquid density. Thus, to successfully employ the methods of this part of ISO 18213, the density of the measured liquid must be determined with sufficient accuracy at its measurement temperature. Therefore, a liquid (such as water) whose density has been very accurately determined at all measurement temperatures is required for calibration. In tanks equipped with two or more dip tubes of differing lengths, it is possible to make accurate determinations of the densities of process liquids from in-tank measurements. The first step is to accurately determine the vertical distance between the two probes (i.e. to calibrate their separation) using a suitable calibration liquid. The probe separation calibration can in turn be used to determine the density of the process liquid in question. Details of this two-stage procedure are presented in ISO 18213-6.

Because liquid density changes with temperature, a height measurement, $H_{1,\mathrm{M}}$, obtained from Equation (8) corresponds to the height of liquid in the tank only at the measurement temperature, T_m. In particular, the height of the liquid used to determine $H_{1,\mathrm{M}}$ is not equal to $H_{1,\mathrm{M}}$ at any other temperature. Moreover, process tanks do not in general have constant cross-sectional areas, so heights determined for a liquid at one temperature are not directly comparable to those determined at other temperatures, even for the same liquid. Therefore, except in very special cases, it is not appropriate to use an equation of the form $H_2 = H_1 \cdot \rho_1/\rho_2$ to make thermal adjustments. In particular, the ratio of the densities of water at two temperatures should not be used to infer the height of process liquid at one temperature from its height at another because unacceptably large errors can result. To ensure that the resulting height determinations are comparable, the standardization steps in Clause 4 should be applied individually to each measurement of pressure.

The value of $H_{1,\mathrm{M}}$ obtained from Equation (8) is valid only at the measurement temperature, T_m. Therefore, it is necessary to standardize the height measurements made at differing temperatures to a fixed reference temperature to compensate for thermally induced changes in the tank and dip tubes. Standardization of several measurements a fixed reference temperature is accomplished as follows. When the liquid in the tank is at temperature T_m, then $H_{1,\mathrm{M}}$ determines a point on the tank wall at the liquid surface. If the tank temperature now changes to T_r, then the elevation of the indicated point (but not the height of the liquid used to determine $H_{1,\mathrm{M}}$) above the tip of the probe changes to

$$H_{1,\mathrm{r}} = H_{1,\mathrm{M}}/(1+\alpha\Delta T_\mathrm{m}) \tag{9}$$

where $\Delta T_\mathrm{m} = T_\mathrm{m} - T_\mathrm{r}$ and α is the linear (thermal) coefficient of expansion of the tank and its probes. To ensure comparability in the presence of temperature variations, all height determinations obtained from Equation (8) should be standardized to a convenient reference temperature (e.g. T_r = 25 °C or T_r = 31 °C) by means of Equation (9). See ISO 18213-2:2007, 5.3 for additional details.

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3) In ISO 18213, all estimates of accuracy are expressed in terms of the half-width of two standard deviation (*95 %)* confidence intervals. Thus, the assertion here is that relative standard deviations for individual measurements in the range 0,005 % to 0,01 % are possible.

4) Depending on the resolution of the manometer, it may be necessary to average the results of several height determinations to achieve this level of precision (see ISO 18213-1:2007, 6.6.3).

An equation has been developed by Jones [8] that relates the differential pressure exerted by a column of water at one temperature to the pressure it exerts at another temperature. A paper by Jones and Crawford [11] describes an experiment which shows that the calculated results are in good agreement with the observed results. For water, this eliminates the need to apply the standardization steps of Clause 4 individually to each pressure measurement. Similar equations can be developed for other liquids, but a safe alternative is to always make the corrections indicated by Equation (8) for each measurement of pressure.

An algorithm is presented in ISO 18213-2 for standardizing a set of data and using these (standardized) data to calibrate a tank (i.e. to estimate the relationship between the response of the tank's measurement system and some independent measure of its liquid content). The procedure specified in this part of ISO 18213 for determining liquid height from pressure is a key step in the overall standardization-and-calibration process. Steps in this part of ISO 18213 are also required when the calibration equation (or its inverse) is subsequently used to determine process liquid volumes (see Clause 7 of ISO 18213-1:2007).

Annex A

(informative)

Estimation of quantities that affect the determination of liquid height

A.1 Introduction

Procedures are presented in this annex for estimating the quantities required to determine liquid height, $H_{1,\mathrm{M}}$, from differential pressure, ΔP_1, by means of Equation (8). In this equation, heights are expressed in meters, pressures are expressed in pascals, and densities are expressed in kilograms per cubic metre. The local acceleration due to gravity, g, is expressed in metres per second squared.

A.2 Liquid density, ρ

Any liquid compatible with the process liquid can be used for tank calibration, provided that accurate measurements of its density can be obtained at all measurement temperatures. Demineralized water is a preferred calibration liquid because its density is well known and can be accurately determined at all temperatures of interest. Equation (A.1) gives very accurate determinations of the density, ρ_M, in kilograms per cubic metre, of air-free (freshly distilled) water for temperatures $T = T_\mathrm{m}$ between 4 °C and 40 °C:

$$\rho_\mathrm{M} = \mathrm{A} + \mathrm{B}T + \mathrm{C}T^2 + \mathrm{D}T^3 + \mathrm{E}T^4 + \mathrm{F}T^5 \qquad \text{(A.1)}$$

where

$\mathrm{A} = 999{,}843\ 22$

$\mathrm{B} = 6{,}684\ 416 \times 10^{-2}$

$\mathrm{C} = -8{,}903\ 070 \times 10^{-3}$

$\mathrm{D} = 8{,}797\ 523 \times 10^{-5}$

$\mathrm{E} = -8{,}030\ 701 \times 10^{-7}$

$\mathrm{F} = 3{,}596\ 363 \times 10^{-10}$

For temperatures between 3 °C and 30 °C, the estimated residual standard deviation for this fit is less than 0,001 kg/m^3. For other temperatures between 1 °C and 40 °C, the reported standard deviation does not exceed 0,001 4 kg/m^3.

Water can become saturated after being exposed to air for a relatively short period of time (approximately 15 h). If necessary, the density of air-saturated water at 1 atm can be calculated by adding the following correction to the estimate obtained from Equation (A.1):

$$\Delta\rho_\mathrm{M} = -4{,}873 \times 10^{-3} + 1{,}708 \times 10^{-4}T - 3{,}108 \times 10^{-6}\,T^2 \qquad \text{(A.2)}$$

Equation (A.2) is applicable for temperatures between 0 °C and 20 °C. The correction for air saturation is –0,002 70 kg/m^3 at 20 °C and its effect diminishes with increasing temperature. The estimated total uncertainty of values calculated with Equation (A.2) is reported as 2×10^{-4} kg/m^3 at the 99 % confidence level. Thus, the effect of air saturation at temperatures greater than 20 °C can safely be ignored for most safeguards applications.

Equations (A.1) and (A.2) are based on a recent re-determination of the density of water [12]. Equation (A.1), or Equation (A.1) and Equation (A.2) in combination, can be used to compute the density of water with sufficient accuracy and precision for safeguards purposes.

If some liquid other than water is used for calibration, then its density must be determined with suitable accuracy at all measurement temperatures before Equation (1) (see Clause 4) can be successfully applied.

Likewise, the use of Equation (8) to determine the height of some process liquid in the tank requires an accurate measure of its density at the measurement temperature. A method for making accurate determinations of liquid density from in-tank measurements is presented in ISO 18213-6.

A.3 Density of gas in the pressure lines

A.3.1 General formula for air density

The density of the gas in the pressure lines is required to evaluate some of the terms in Equation (8). If the gas is air, then its density, ρ_a, in kilograms per cubic metre, can be determined from its temperature, pressure and relative humidity by means of Equation (A.3)[10]:

$$\rho_a = \frac{(0{,}003\,484\,7)}{(T+273{,}15)}\left[P - 6{,}653\,06 \times 10^8 \times U \times e^{\left(\frac{-5\,315{,}56}{T+273{,}15}\right)}\right] \tag{A.3}$$

where

P is the pressure, in pascals;

U is the relative humidity of the air, in percent saturation;

T is the average temperature of the gas, in degrees Celsius.

If the bubbling gas is not air (e.g. N_2), then a suitable alternative to Equation (A.3) is required. In any case, Equation (A.3) can also be used to estimate the density of the air in the tank above the liquid surface.

A.3.2 Density of air in the major probe line, $\rho_{a,1}$

Measurements of P (Pa), U (% saturation), and T (°C) are required to use Equation (A.3) for estimating the density of air in the major probe line. If measurements are not available, the following default values will yield acceptable results in nearly all cases.

A suitable default value for P is

$$P = \Delta P_1 + P_s \tag{A.4}$$

where

ΔP_1 is the observed differential pressure at the manometer;

P_s is the barometric pressure minus off-gas pressure.

Standard atmospheric pressure at sea level is $1{,}013\,25 \times 10^5$ Pa, and typical off-gas pressure is 500 Pa, equivalent to the pressure exerted by a 50 mm column of water. If these values are used in Equation (A.4), the result is

$$P = \Delta P_1 + 1{,}008\,25 \times 10^5 \tag{A.5}$$

In practice, when standard atmospheric pressure is used in Equation (A.4) (and elsewhere) to estimate P_s, it should be adjusted to account for the elevation of the facility above sea level and also, if possible, for the actual off-gas pressure. Since variations in atmospheric pressure will generally have the greatest effect on results, it is desirable to use actual measurements of atmospheric pressure whenever possible.

Suitable default values for U and T are

$U = 20$ % saturation (if the bubbling gas is dry) or $U = 80$ % saturation (if the bubbling gas is wet);

$T = 25$ °C.

The average of the ambient temperature and the temperature of the tank liquid can be used as an alternative to a standard value for T.

A.3.3 Density of air in the reference probe line, $\rho_{a,r}$

As with the major probe, suitable measurements of P, U, and T are required to use Equation (A.3) for estimating the density of air in the reference probe line. The following default values for P (Pa), U (% saturation), and T (°C) will yield acceptable results in nearly all cases:

$P = P_s = 1{,}008\ 25 \times 10^5$ Pa;

$U = 20$ % saturation (dry bubbling gas) or $U = 80$ % saturation (wet bubbling gas);

$T = 25$ °C.

The current ambient temperature can be used as an alternative to a standard value for T.

A.3.4 Density of air in the tank, $\rho_{a,s}$

The density of air in the tank above the surface of the liquid can be estimated from Equation (A.3) with the aid of the following values for P (Pa), U (% saturation), and T (°C):

$P = P_s = 1{,}008\ 25 \times 10^5$ Pa;

$U = 50$ % saturation (if the bubbling gas is dry) or $U = 90$ % saturation (if the bubbling gas is wet);

T is the temperature of the liquid in the tank.

A.4 Quantities associated with bubble formation, r_b, λ and σ

Quantities associated with bubble formation at the tip of the major probe include the distance of the lowest point of the bubble below the tip of the major probe, λ, the radius of curvature of the bubble at its lowest point, r_b, and the surface tension for the liquid and bubbling gas, σ.

Suitable estimates of r_b and λ are

$r_b = 0{,}75d = 3d/4$

$\lambda = d/3$

where d is the inner diameter of the bubbling probe, in metres.

If the liquid in the tank is water and the bubbling gas is air, then the surface tension at the air-water interface, σ, in newtons per metre, can be estimated by means of Equation (A.6) [8]:

$$\sigma = 75{,}675 \times 10^{-3} - 1{,}376\,2 \times 10^{-4} T - 3{,}938 \times 10^{-7} T^2 + 1{,}076 \times 10^{-9} T^3 \qquad \text{(A.6)}$$

where T is the temperature of the tank liquid, in degrees Celsius.

An alternative model to that proposed here is given in Reference [7]. The two models yield very similar results and may be used interchangeably.

A.5 Elevations, E_1 and E_r

It is necessary that the elevations, E_1 and E_r, of the manometer above the tips of the major and reference probes in metres, respectively, be measured or determined from engineering drawings. There are no default values for these quantities.

A.6 Pressure drop, $\delta_1 - \delta_r$

The difference in pressure drop between the major probe and reference probe lines, $\delta_1 - \delta_r$, can be equalized operationally. This is done by setting air flow rates differentially so as to equalize the pressure drop in the two lines when the tank is empty.

Alternatively, the pressure drop in the probe lines, δ, in pascals, due to flow resistance can be estimated by means of Poiseuille's Equation [15]

$$\delta = 128\pi^{-1} \mu L Q / d^4 \qquad \text{(A.7)}$$

where

μ is the viscosity of the gas flowing through the line, in pascal seconds;

L is the length of the line through which the gas flows, in metres;

Q is the volume flow rate of the gas through the line, in cubic metres per second;

d is the inner diameter of the major probe, in metres.

If both the major and reference tubes have the same inner diameter, then the difference in pressure drop between the two lines is given by Equation (A.8):

$$\delta_1 - \delta_r = 128\pi^{-1} \left(\mu_1 L_1 Q_1 - \mu_r L_r Q_r \right) \big/ d^4 \qquad \text{(A.8)}$$

where the subscripts “1” and “r” refer respectively to the (major) bubbling probe and the reference probe.

The viscosity, μ, in pascal seconds, of air can be calculated from temperature and pressure by means of Equation (A.9)[5]5)

$$\mu = 1{,}702\,57 \times 10^{-5} + 6{,}054\,34 \times 10^{-8} T - 1{,}332\,00 \times 10^{-10} T^2 + 1{,}172\,37 \times 10^{-13} P + 1{,}256\,39 \times 10^{-20} P^2 \qquad \text{(A.9)}$$

where

T is the temperature of the tank liquid, in degrees Celsius;

P is the pressure, in pascals.

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5) Nitrogen is often used as the bubbling gas instead of air. The viscosity of nitrogen and several other gases is also given in Reference [9].

The pressure in the reference probe can be estimated by (see A.3.3):

$$P = P_s = 1{,}008\ 25 \times 10^5 \text{ Pa}$$

and the pressure in the major probe can be estimated by (see A.3.2):

$$P = \Delta P_1 + P_s = \Delta P_1 + 1{,}008\ 25 \times 10^5 \text{ Pa}$$

The current ambient temperature can be used to estimate the temperature in the reference probe (see A.3.3). The average of the ambient temperature and the temperature of the tank liquid can be used to estimate the average temperature in the major probe line (see A.3.2).

Values for Q_1 and Q_r, the flow rates of gas in the major and reference probe lines, are observed from flow meters connected to the respective probe lines. Alternatively, a nominal gas flow rate (e.g., 5×10^{-5} m^3/s at standard temperature and pressure) may be used to estimate these quantities.

The lengths, L_1 and L_r, of the major and reference probes lines, respectively, shall either be measured or determined from engineering drawings. If the lines between the tank and the manometer are essentially vertical, without any significant horizontal sections, then E_1 and E_r provide suitable values for L_1 and L_r, respectively (see A.5).

A.7 Local acceleration due to gravity, g

The local acceleration due to gravity depends on elevation and latitude, and should be determined at the measurement site. In lieu of an on-site determination, the local acceleration due to gravity may be determined with suitable accuracy from charts in Appendix 7 of Reference [13]. An erroneous value will produce a bias in the resulting height determination that is approximately proportional to the error in the determination of the local acceleration due to gravity. In any event, the same value should be used for all measurements of both calibration and process liquids to ensure internal consistency among measurements.

A.8 Coefficient of linear expansion, α

The linear (thermal) coefficient of expansion for the tank and its probes is required to standardize height determinations to a convenient reference temperature as indicated in Clause 5. If it is not possible to determine the type of material from which the tank is constructed, then the coefficient of linear expansion for Type 304 stainless steel may be used (provided the tank is made of steel). This coefficient has the value $\alpha = 1{,}728 \times 10^{-6}$ °C[14].

A.9 Note on use of default values

Whenever possible, the quantities required to apply Equation (8) should be measured. However, where measurement is impossible or impractical, the default values suggested in this annex will give acceptable results under normal operating conditions in nearly all cases. For certain parameters, such as atmospheric pressure and the local acceleration due to gravity, systematic biases are introduced when standard values are used in place of actual measurements. These biases have no effect on comparisons within a facility, provided that the same values are used for all calculations, but they may become significant when measurements from facilities at several different locations are compared or combined. In this case, local determinations of the relevant parameters should be employed to ensure that the results generated by means of Equation (8) remain comparable.

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