

# Baumer Guideline for Hydrostatic Level Measurement

## Scope

This document describes how hydrostatic level measurement works, i.e. the use of pressure sensors to determine the continuous level in a container. It is intended to deepen the understanding of this measuring method and to give the user a check for suitability in his application. Furthermore, it enables him to make the correct selection of suitable sensors and measuring ranges. Furthermore, the attainable accuracy under certain conditions is discussed and instructions for evaluating the measuring signals are given. An appendix with the theoretical derivation of the used variables and formulas allows to deal with the matter in more detail if necessary.

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## 1 Abstract

### 1.1 Application area of the measurement

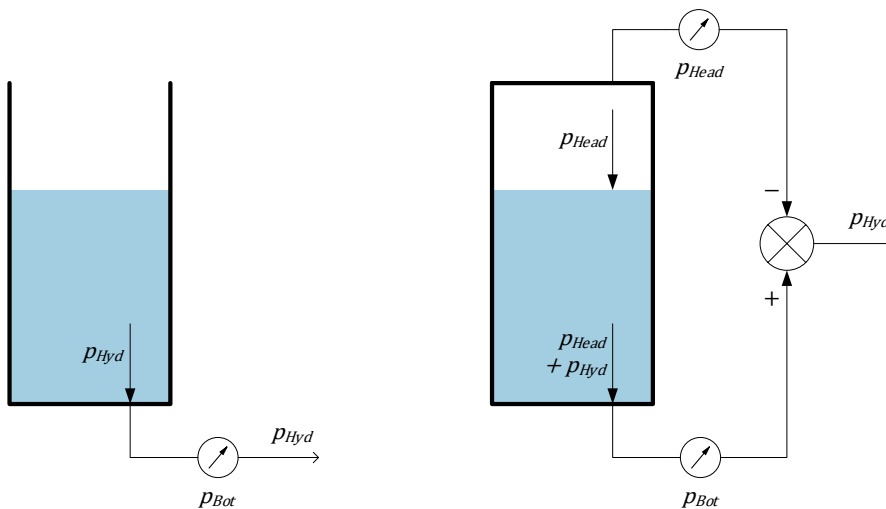
Pressure sensors can be used to measure the continuous level of a liquid medium in a container. This measuring principle is the most frequently used level measuring method. In process automation, almost half of all continuous level applications are implemented with pressure sensors.

### 1.2 Physical mode of operation

A water column with a height of 10 m exerts a pressure of approx. 1 bar on its base. This means a pressure change of approx. 1 mbar per 1 cm level change. For media other than water, a correspondingly different relationship applies due to their different density. In practice, the values lie between 0,8 mbar / cm for oils and 1,3 mbar / cm for glycerin.

### 1.3 Properties of the measuring principle

- The pressure sensor for measuring the hydrostatic pressure  $p_{Hyd}$  must be installed in the area of the tank bottom, as no level measurement is possible below the pressure sensor position.
- When the tank is closed, an additional pressure sensor in the head of the tank is required to compensate for the so-called "head pressure"  $p_{Head}$ .

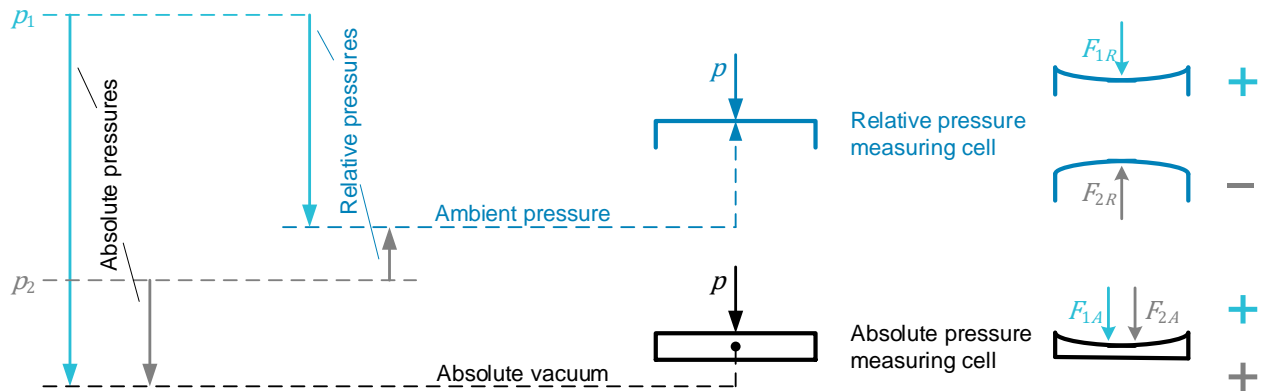


**Figure 1: Principle of hydrostatic level measurement with open and closed container**

- The measuring principle is not influenced by:
  - Foam on the surface
  - Turbulent surface
  - Fast level change
  - Installations
- To calculate the level from the measured pressure, the specific density of the medium must be known. In case of large temperature fluctuations of the medium and high required accuracy, the temperature must also be measured to compensate the temperature dependence of the density.

## 1.4 Definition of pressure designations

In practice, certain terms have been coined to describe what a pressure is called under certain conditions. Figure 2 shows an example of two pressures  $p_1$  and  $p_2$  and the effect on a "relative pressure cell" and an "absolute pressure cell" respectively.



**Figure 2: Pressure relations for relative and absolute pressure measurement**

When talking about "relative pressure" or "absolute pressure", one refers to the reference used as a basis, namely whether the pressure is meant against "ambient pressure", generally air pressure, or against "absolute vacuum". The same pressure, e.g.  $p_1$  in Figure 2, then receives different numerical values.

- "Relative pressure"
 

The back of the diaphragm on the "relative pressure measuring cell" is in contact with the ambient pressure. This pressure counteracts the externally applied pressure  $p$ . In the example shown,  $p_1$  is greater than the ambient pressure, the diaphragm is pressed inwards ( $F_{1R}$ ), which gives a positive measurement result. In the opposite case, pressure  $p_2$  is lower than the ambient pressure; the diaphragm is pressed outwards ( $F_{2R}$ ), which gives a negative measurement result. This is called "negative pressure" or also, incorrectly, "vacuum".
- "Absolute pressure"
 

Inside the closed "absolute pressure measuring cell" there is "absolute vacuum", i.e. the back of the diaphragm is without material and therefore completely pressureless. The diaphragm is pressed inwards at any pressure  $p$  ( $F_{1A}$ ,  $F_{2A}$ ). If vacuum is applied as pressure  $p$ , the diaphragm is relieved and the measuring result is 0 bar abs. There can thus be no negative values for "absolute pressure".

### Example:

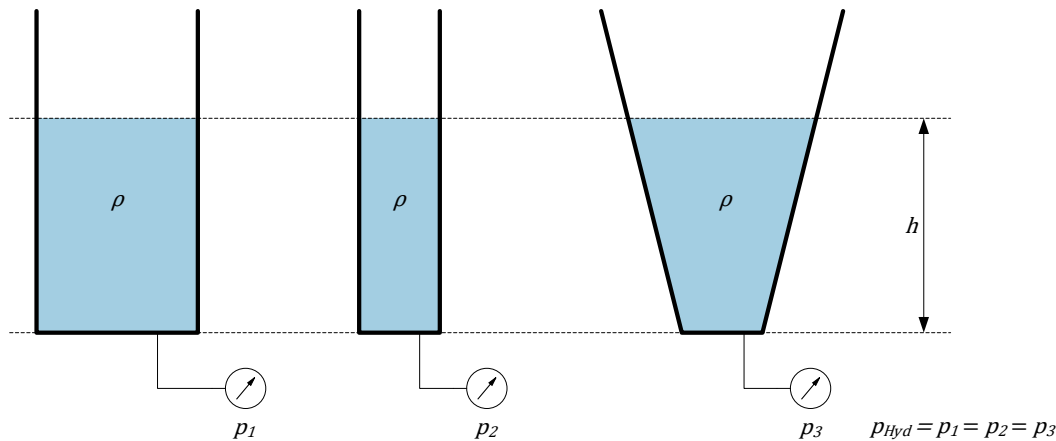
Pressure type (Unit)	Relative pressure (bar)	Absolute pressure (bar)	Relative pressure (psi)	Absolute pressure (psi)
Ambient pressure	0,00 bar	1,0 bar abs	0 psig	14 psia
<b>p1</b>	1,4 bar	2,4 bar abs	19 psig	33 psia
<b>p2</b>	-0,3 bar	0,7 bar abs	-4 psig	10 psia

There is also the pressure designation "differential pressure". This refers to the difference between two pressures. So-called "differential pressure measuring cells" have two connections for the supply of the two pressures, each connected to one side of the diaphragm. Nowadays, these complex measuring cells are often replaced by two individual pressure sensors by calculating the pressure difference from the individual pressure measured values. This is also the principle behind the compensation of the "head pressure".

## 2 Physical relationship

### 2.1 Hydrostatic Paradoxon

As the fill level  $h$  increases, a liquid exerts an increasing hydrostatic pressure  $p_{Hyd}$  on a pressure sensor mounted at the bottom of the container. If the density  $\rho$  of the liquid is homogeneous, the correlation is linear and independent of the container's geometry (Hydrostatic Paradoxon).



**Figure 3: Independence of hydrostatic pressure from vessel geometry**

In practice, it is often not the level but the volume in a container that is of interest. As can be easily seen in Figure 3, the relationship between volume and level depends on the vessel geometry. In non-cylindrical tanks, the relationship is non-linear. The volume can be calculated theoretically from the level via a formula or determined via calibration and the storage of a linearization table.

### 2.2 Relationship between level and hydrostatic pressure

The formula derivation between fill level  $h$ , hydrostatic pressure  $p_{Hyd}$  and density  $\rho$  can be found in the appendix as also formulas with imperial units. The correlation applies:

$$h = 10.2 \cdot \frac{p_{Hyd} [\text{bar}]}{\rho \left[ \frac{\text{kg}}{\text{dm}^3} \right]} \text{ m}$$

The greater the density  $\rho$  of the liquid, the greater the measured pressure  $p_{Hyd}$  at the same level  $h$ . Therefore, the pressure must be divided by the density of the liquid to obtain the level in meters. For a measured pressure of 1 bar, the following is obtained for water assuming a density of 1 kg per liter ( $\text{dm}^3$ ):

$$h = 10.2 \cdot \frac{1 \text{ bar}}{1 \frac{\text{kg}}{\text{dm}^3}} = 10.2 \text{ m}$$

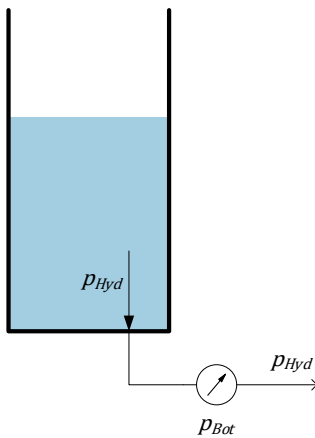
A fill level of about 10 m therefore generates a pressure of 1 bar for water (rule of thumb: 1 mbar per cm). This pressure is relatively low, since pressure sensors with 1 bar are already among the more sensitive measuring ranges. Smaller measuring heights require even smaller measuring ranges. For tank heights less than 1 m, accurate measurements are practically only possible by adapting to local conditions. This requires highly sensitive pressure sensors with a measuring range  $\leq 0.1$  bar.

### 3 Applications

#### 3.1 Open container

An open container has an opening, even if only small, to the environment (ventilation). This means that the ambient pressure (barometric pressure) prevails in the head of the container. Since the ambient pressure also presses on the liquid surface, only the pressure generated by the liquid is of interest. This is why only pressure sensors with relative pressure measuring cells, i.e. those with ambient pressure compensation, are used for open containers. The evaluation unit can directly use the measured pressure value  $p_{Bot}$  of the sensor mounted at the bottom of the container to calculate the fill level:

$$p_{Hyd} = p_{Bot}$$



**Figure 4: Direct hydrostatic pressure measurement in an open container**

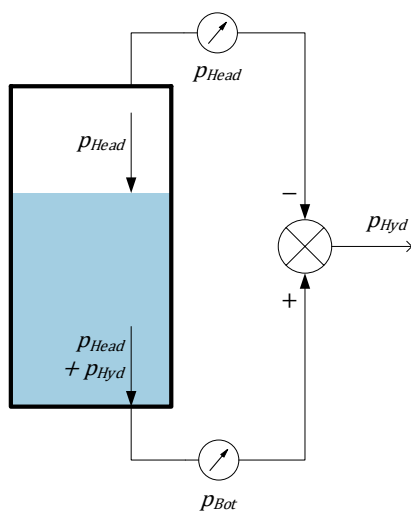
### 3.2 Closed container

The previous consideration assumes that the tank is pressureless, i.e. that there is at least a small opening (ventilation) to the environment at the top. If the container is closed, a gas pressure different from the ambient pressure develops in the container volume above the liquid, caused by its gas phase, temperature changes, fermentation, addition of protective gas or filling and emptying, e.g. by pressing with gas.. This so-called "head pressure"  $p_{Head}$  must be measured and taken into account mathematically.

The purely hydrostatic pressure  $p_{Hyd}$  is then calculated as follows:

$$p_{Hyd} = p_{Bot} - p_{Head}$$

The evaluation unit must therefore calculate the difference between the two measured values.



**Figure 5: Indirect hydrostatic pressure measurement in a closed container**

The pressure sensors and their measuring ranges must be selected so that the overload limit is not reached on the one hand and the sensitivity is still sufficient on the other. If the head pressure  $p_{Head}$  is small compared to the hydrostatic pressure  $p_{Hyd}$ , the procedure is not critical. However, head pressures are often higher than the hydrostatic pressure. The larger measuring ranges to be selected reduce the accuracy for the relatively small proportion of the hydrostatic pressure. This means that the full-scale errors of the large measuring ranges have an effect on the relatively small modulation of the level measurement. Sensors with high measuring accuracy (e.g. max. measuring error 0.1 %) and excellent temperature stability (e.g. 0.03 % / 10 K) can help here.

Example:

Water level max. 3 m, head pressure max. 3.5 bar. Sensors with a measuring range of 4 bar should be selected. The max. measuring deviation including temperature drift is assumed to be 0.5 % FS. Since two sensors are calculated, the measurement deviations of both sensors must be added together. This results in an absolute error of 4 bar x 1 % = 40 mbar for the maximum measuring deviation of the determined pressure difference. Based on the hydrostatic pressure of almost 300 mbar, this corresponds to a relative error of 40 mbar / 300 mbar = 12.5 % for level measurement. This will not be acceptable for most applications. The rule of thumb for a maximum error of 3 % is the assumption that the head pressure should not be greater than twice the value of the hydrostatic pressure. In our example this would be the case:

Water level max. 3 m, head pressure max. 0.6 bar. Sensors with a measuring range of 1 bar should be selected.

Absolute error: 1 bar x 1 % = 10 mbar. Relative error: 10 mbar / 300 mbar = 3.3 %.

### 3.3 Container with negative pressure (vacuum)

It is also important to consider the possible formation of a negative pressure in the tank. This can be caused, for example, by temperature changes or pumping processes. Pressure sensors that have a measuring range starting from zero can either output no negative pressure values at all (with 0 – 10 V voltage output signal) or only very low negative pressure values, usually -1% (with 3.8 mA current output signal). Very low negative pressures must also be taken into account, as even 1 mbar causes a change in the hydrostatic level determination of 1 cm. For example, a negative pressure of -20 mbar at a maximum fill level of 2 m would cause an error of 10 % if the negative pressure were not measured correctly because the signal of the pressure sensor moves to the lower signal stop. It is therefore important to check whether negative pressures to the environment can occur. In this case, pressure sensors must be selected with a measuring range that covers the negative range accordingly (e.g. -0.1 to +0.5 bar). The evaluation unit must be able to take negative numerical values into account for the calculation.

Example:

Measuring range of both pressure sensors with 4-20 mA current output: -1 to +1 bar

Normalization for internal calculation (scaling): 4 mA = -1000.0; 20 mA = +1000.0

Water level: 1 m; head pressure: -200 mbar

Head pressure sensor measures -200 mbar and signals 10.400 mA:

scaled measured value reading = -200.0

Bottom pressure sensor measures 98.1 mbar - 200 mbar = -101.9 mbar and signals 11.185 mA:

scaled measured value reading = -101.9

Differential pressure calculation:  $-101.9 - (-200.0) = +98.1$ : corresponds to hydrostatic pressure of liquid

In most cases, sensors with a relative pressure measuring cell are also suitable here because the measuring range can be selected to be smaller by the ambient pressure of approx. 1 bar.

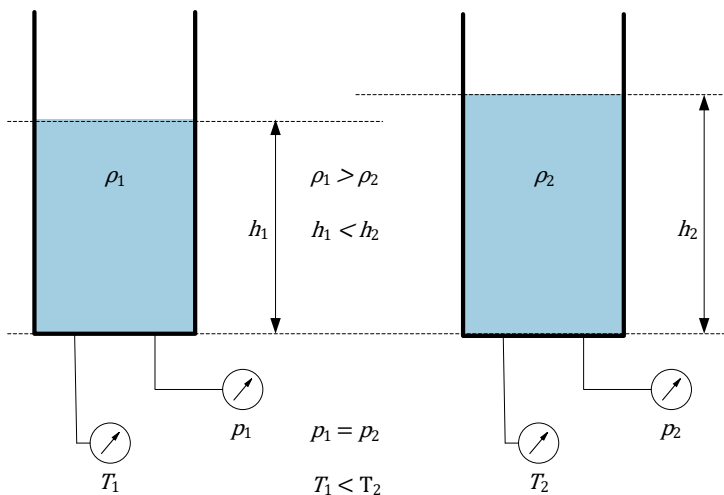
For vacuum applications where the head pressure is constantly lower than the ambient pressure, sensors with absolute pressure measuring cell can also be used to advantage. In these applications the measurement of the absolute pressure, i.e. against vacuum, is of interest anyway.

Further applications for absolute pressure measurements are vapor pressure measurement with simultaneous level measurement or areas where high humidity and frequent changes of process temperatures can cause problems with condensate in the pressure compensation system of a relative pressure measuring cell.

## 4 Signal evaluation

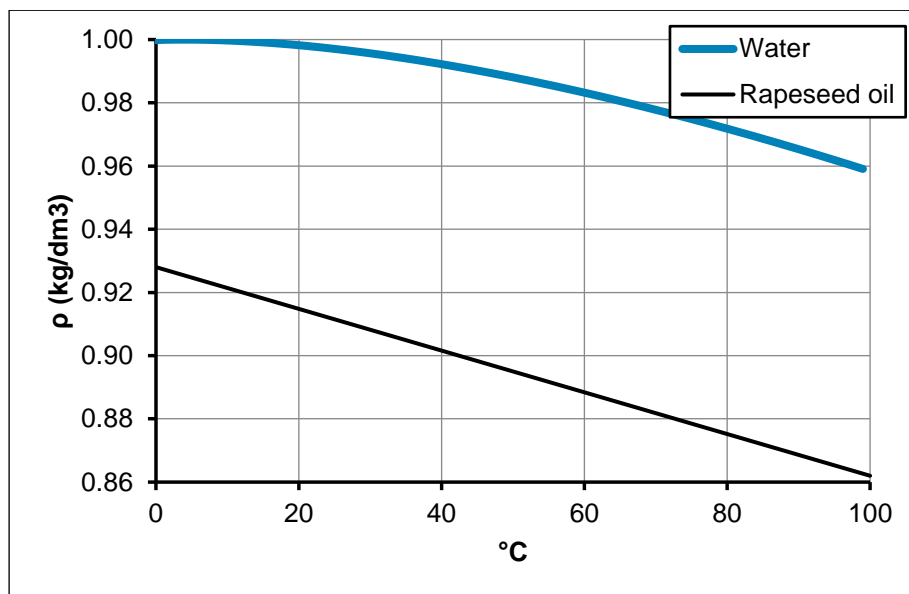
### 4.1 Consideration of the specific density

For accurate hydrostatic level measurement, the specific density of the medium used must be included in the level calculation. The specific density of a medium is also temperature-dependent. Figure 6 shows the relationships when the temperature of a medium changes from  $T_1$  to  $T_2$ . In the right tank the temperature  $T_2$  of the same medium is higher. Due to the temperature expansion of the medium, it takes up more volume and thus the level rises from  $h_1$  to  $h_2$ . However, the hydrostatic pressure  $p_1 = p_2$  remains unchanged, because the density of the medium decreases from  $\rho_1$  to  $\rho_2$  at the same time.



**Figure 6: Level change due to temperature change of the same medium**

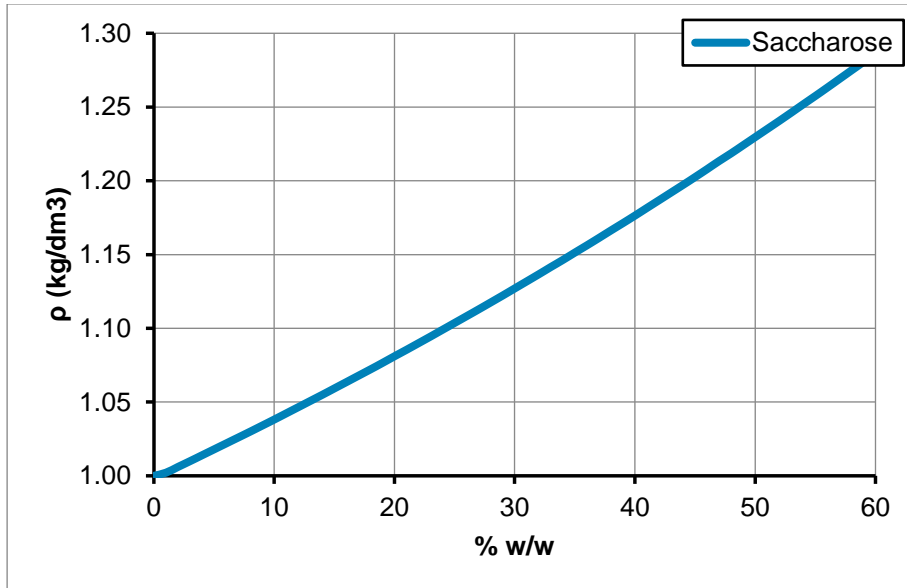
Figure 7 shows the specific values of the density of water and rape seed oil versus temperature. Compared to water with a density of  $1 \text{ kg / dm}^3$ , rapeseed oil, has only approx.  $0.915 \text{ kg / dm}^3$ . The measured pressure is then 8.5 % lower for the same fill level. The temperature dependence of water is nonlinear; between  $0 \text{ }^\circ\text{C}$  and  $100 \text{ }^\circ\text{C}$  the density changes by about -4 %. The density of oils decreases practically linearly with temperature; as a reference value this is approx.  $-0.7 \text{ \% / 10 K}$ .



**Figure 7: Specific density of water and rapeseed oil as a function of temperature**



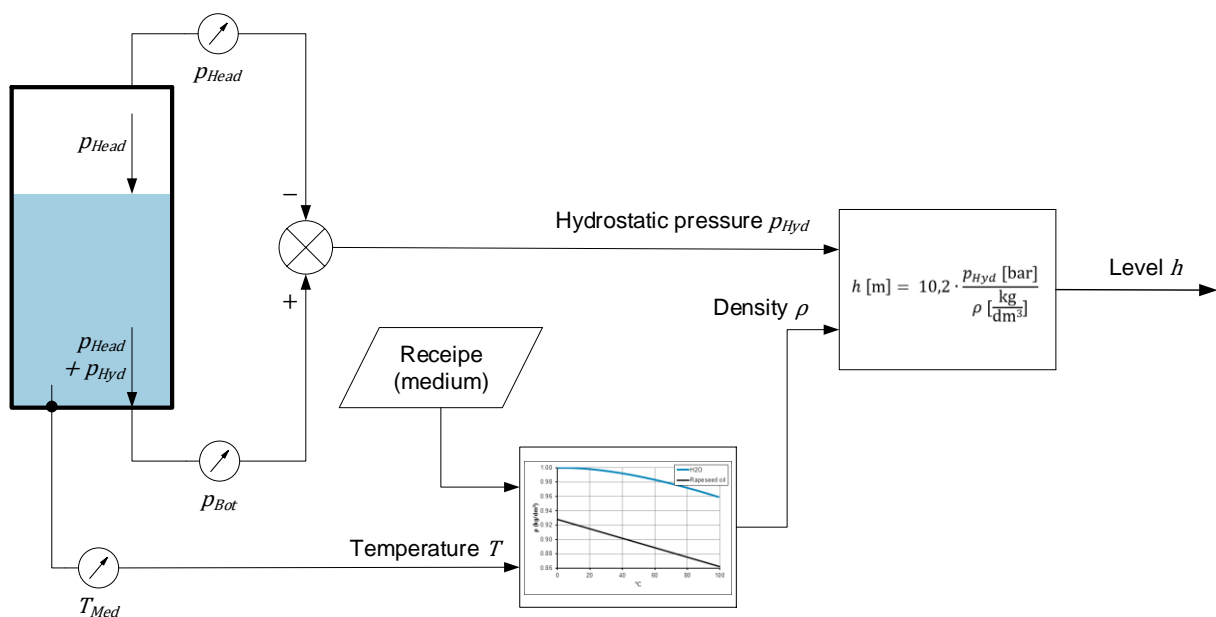
If the systematic measurement deviation cannot be tolerated due to the temperature dependence of the density, the medium temperature must also be measured and the corresponding calculation specification for the density stored. If different media are used in a system, the corresponding density for each medium (or recipe) must be included in the level calculation. This is the case, for example, if different concentrations of sugar are present, as is often the case with soft drinks. Figure 8 shows the relationship between weight concentration and density of saccharose in water.



**Figure 8: Specific gravity of saccharose as a function of weight concentration**

## 4.2 Signal flow

The circuit diagram in Figure 9 shows all possible parameters for calculating the fill level. Depending on the application, certain parameters can be omitted, e.g. temperature measurement for temperature compensation of the density with only small temperature fluctuations of the medium, head pressure sensor with open tank or information on the recipe for density determination with non-changing medium.



**Figure 9: Signal flow for level calculation under consideration of all parameters**

## 5 Conclusion

### 5.1 Suitability of the measuring method

The hydrostatic level measurement can be an elegant solution for the continuous fill level measurement, if certain conditions are fulfilled and corresponding boundary conditions are considered.

### 5.2 Prerequisites and boundary conditions

This checklist is intended to check whether the prerequisites and boundary conditions for a reliable hydrostatic level measurement are fulfilled.

#### 5.2.1 Container and process properties

- It is always necessary to install a pressure sensor in the bottom area of the tank. It should be noted that with pressure vessels, a (renewed) test is necessary after welding in a process connection.
- With a closed container, the head pressure must be measured with an additional pressure sensor and included in the level calculation.
  - The head pressure should not be more than twice the hydrostatic pressure. Otherwise the max. measuring deviation of the calculated level can become unacceptable, since the relative measuring deviations of the pressure sensors always refer to their (then very large) pressure measuring ranges.
  - The max. measuring deviations of both pressure sensors add up in the worst case. The max. measuring deviation of the calculated level can therefore be considerably higher. For this reason, pressure sensors of the highest possible precision should be used. The max. measuring deviation of the calculated level should be determined in advance, taking into account all specified pressure sensor parameters, i.e. also temperature and long-term drift.
  - With a standard pump inlet pressure of 2 bar, a measurement deviation in the range of 10 – 20 cm must be expected even when using high-precision pressure sensors. With flat tank bottoms this can still mean a considerable residual volume.
  - If the head pressure can assume a negative pressure in relation to the ambient pressure, the measuring ranges of the sensors must be designed for a corresponding negative pressure range. In addition, the suitability of all components must be checked for appropriate vacuum resistance.
  - The head pressure sensor can be advantageously installed in a tank dome.
  - Paddles of agitators can generate pressure waves and thus influence the measurement.

#### 5.2.2 Media properties

- The density of the medium must be taken into account in the calculation. With changing media, the medium must be known to provide the corresponding density value.
- The density depends on the temperature. For exact level measurements, the medium temperature must also be measured and the density value corrected accordingly.
- In case of settling ingredients, e.g. yeast and pulp, the pressure sensor may be covered. Considerable measuring errors can occur due to:
  - Covering the membrane of the sensor element
  - Inhomogeneity in the medium (variable density)
  - Remaining sediment layer on membrane after tank emptying

#### 5.2.3 Sensor properties

- The hydrostatic level measurement is not suitable for realizing an exact empty signal, e.g. for a dry run protection for pumps, because the measured values for very small filling levels can already be in the

range of the expected max. measuring deviations. For this reason, a separate level switch for point level detection or empty pipe monitoring must be used for this function.

- Pressure sensors have specified a so-called "compensated temperature range". This is important for the process temperature range where accurate measurements are of interest. The total allowable process temperature range is normally larger and is used for survival in high temperature process steps, e.g. SIP cleaning cycles.
- In applications with intense hot/cold changes, condensation problems can occur in the pressure sensor. In such cases, the use of so-called "condensate-resistant" pressure sensors is recommended. These more elaborately designed pressure sensors have a closed diaphragm system to compensate the ambient pressure and the electronics are additionally protected against condensate, e.g. by potting. Sensors with absolute pressure measuring cells are more robust against condensate due to the missing connection to the ambient pressure, provided that the electronics are sufficiently protected. However, due to the necessarily larger measuring ranges (+ 1 bar), a larger measuring deviation must be accepted.

### 5.3 Advantages

- Non-invasive sensor element (front-flush)
- High acceptance of various liquid and pasty (homogeneous) media
- No limitation regarding conductivity and dielectric constant
- Short reaction time possible (several ms)
- No interference by foam (is measured integrally with)
- Insensitive to unstable liquid surfaces (agitators, etc.)
- No influence of container geometry and internals on the measuring performance
- Different technologies and designs available

### 5.4 Drawbacks

- Depending on the density of the medium
- Unsuitable for solids
- For small containers (height < 1 m) only recommended with adaptation to the conditions
- Closed containers require second sensor and process connection
- Conditionally suitable for high head pressures (greater than 2 x hydrostatic pressure)
- Installation in the bottom area of the tank necessary
- Medium in direct contact with the sensor: check the chemical resistance of the materials as well as the wear caused by abrasive media

## 6 Appendix

### 6.1 Formula derivation (metric)

$$\text{Hydrostatic pressure } [p_{Hyd}] = 1 \frac{\text{N}}{\text{m}^2} = 1 \frac{\text{kg}}{\text{m} \cdot \text{s}^2} = 10^{-5} \text{ bar}$$

$$\text{Force } [F] = 1 \text{ N} = 1 \frac{\text{kg} \cdot \text{m}}{\text{s}^2}$$

$$\text{Density } [\rho] = 1 \frac{\text{kg}}{\text{m}^3} = 10^{-3} \frac{\text{kg}}{\text{dm}^3}$$

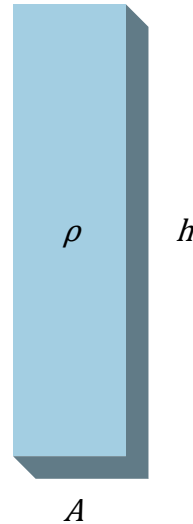
$$\text{Area } [A] = 1 \text{ m}^2$$

$$\text{Height } [h] = 1 \text{ m}$$

$$\text{Mass } [m] = 1 \text{ kg} \quad m = \rho \cdot A \cdot h$$

$$\text{Gravity } [g] = 1 \frac{\text{m}}{\text{s}^2} \quad g = 9,81 \frac{\text{m}}{\text{s}^2}$$

Liquid column



The pressure  $p_{Hyd}$  (also called "gravity pressure" in this context) results from the force  $F$  per area  $A$ . The mass  $m$  of the liquid column, depending on the volume  $A \cdot h$  and the density  $\rho$ , generates the weight force  $F$  via the acceleration due to gravity  $g$ .

$$p_{Hyd} = \frac{F}{A} = \frac{m \cdot g}{A} = \frac{\rho \cdot A \cdot h \cdot g}{A} = \rho \cdot h \cdot g$$

Hydrostatic paradox:

Area  $A$  is no longer included in the result for the relation of pressure  $p_{Hyd}$  to density  $\rho$  and height  $h$  of the liquid column. This illustrates the independence of the pressure from the container geometry. Simplified it can be said that with increasing area of the liquid column its mass increases and thus exerts a greater weight force, but this is distributed over a larger area, which in turn causes a smaller pressure.

$$h = \frac{p_{Hyd}}{\rho \cdot g} = \frac{p_{Hyd} [\text{bar}] \cdot 10^5 \frac{\text{kg}}{\text{m} \cdot \text{s}^2}}{\rho \left[ \frac{\text{kg}}{\text{dm}^3} \right] \cdot 10^3 \frac{\text{kg}}{\text{m}^3} \cdot 9,81 \frac{\text{m}}{\text{s}^2}} = 10,2 \cdot \frac{p_{Hyd} [\text{bar}]}{\rho \left[ \frac{\text{kg}}{\text{dm}^3} \right]} \text{ m}$$

The constant factor 10.2 is thus calculated from the reciprocal of the acceleration due to gravity and the size adjustment of the units.

## 6.2 Formula derivation (imperial)

$$\text{Hydrostatic pressure } [p_{Hyd}] = 1 \frac{\text{lb}_F}{\text{in}^2} = 1 \text{ psi}$$

$$\text{Force } [F] = 1 \text{ lb}_F$$

$$\text{Specific weight } [\gamma] = 1 \frac{\text{lb}_F}{\text{ft}^3} = \frac{1}{7.48} \cdot \frac{\text{lb}_F}{\text{gal US}}$$

$$\text{Length, height } [l, h] = 1 \text{ ft} = 12 \text{ in}$$

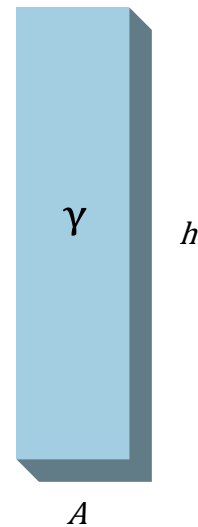
$$\text{Area } [A] = [l^2] = 1 \text{ in}^2 = \frac{1}{12^2} \text{ ft}^2 = \frac{1}{144} \text{ ft}^2$$

$$p_{Hyd} = \frac{F}{A} = \frac{\gamma \cdot A \cdot h}{A} = \gamma \cdot h$$

$$h = \frac{p_{Hyd}}{\gamma} = \frac{p_{Hyd} [\text{psi}] \cdot \frac{1}{144} \text{ ft}^2}{\gamma \left[ \frac{\text{lb}_F}{\text{ft}^3} \right] \cdot \frac{\text{lb}_F}{\text{ft}^3}} = 144 \cdot \frac{p_{Hyd} [\text{psi}]}{\gamma \left[ \frac{\text{lb}_F}{\text{ft}^3} \right]} \text{ ft}$$

$$h = 144 \cdot \frac{p_{Hyd} [\text{psi}]}{\gamma \left[ \frac{1}{7.48} \cdot \frac{\text{lb}_F}{\text{gal US}} \right]} \text{ ft} = 19.25 \cdot \frac{p_{Hyd} [\text{psi}]}{\gamma \left[ \frac{\text{lb}_F}{\text{gal US}} \right]} \text{ ft}$$

Liquid column



Please note, that formulas given with imperial units use specific weight  $\gamma$  instead of specific (mass) density  $\rho$ .

Relation between units “psi” and “bar”:

$$1 \text{ bar} = 14.503773773 \text{ psi} \quad 1 \text{ psi} = 0.068947573 \text{ bar}$$

Precise value for the standard gravity:

$$g = 9.80665 \frac{\text{m}}{\text{s}^2}$$



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**6.4 Documentation history**

Version	Date	Reviewed by	Amendment / Supplement / Description
V1.10	25.05.2020	fep	Translation from German document V1.10 DE