

## How useful are steam measurements in the wet steam area?

Most steam flow measurements are carried out pressure and temperature compensated in the superheated area. But there is also a large amount of so-called saturated steam measurements which take place either pressure or temperature guided. Here, the saturated steam temperature or pressure appears as reference variable of the corresponding saturated pressure or temperature. At a specific saturated steam temperature a specific boiling pressure is allocated to the steam according to the steam pressure curve. A specific steam volume (steam density) is determined from this using the steam table. In classic differential pressure methods, the steam flow to be measured strongly depends on this specific steam volume. Practice has quite often shown that many operators assume saturated steam conditions although the actual fluid state is no longer the same as the theoretical saturated steam conditions. In many cases the steam is slightly sub-cooled and there is already a 2-phase flow since the steam state is in the wet steam area. Steam flow measurements in this area lead to large inaccuracies compared to steam measurements in the homogeneous area (dry-saturated/superheated).

The thermodynamic processes in the wet steam area are explained below by means of the thermodynamic basics. Condensation processes in steam lines are additionally explained together with the resulting problems for steam measurements.

Solutions for achieving a precise and reliable steam measurement will be subsequently proposed.

## Thermodynamic basics

A pure medium (e.g. water) can have different aggregation states. Each pure medium is therefore characterised by thermal state surfaces. The state surfaces are often represented on the p-V level (pressure/volume level).

In these representations, phase transitions or aggregate changes can be illustrated in a simple form. Special identifiers are used for this. (fig. 1)

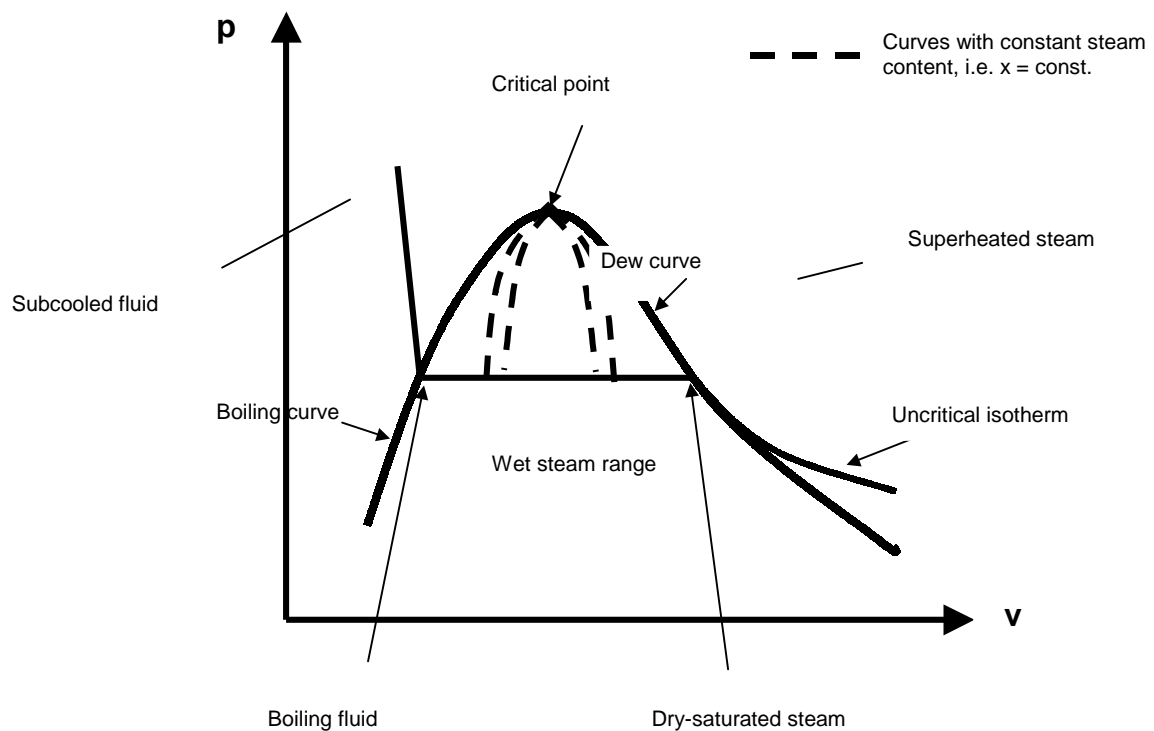


Figure 1: Identifiers in the p- v diagram

The following definitions apply:

Isotherms: Constant temperature curve

Steam: Condensable gas

Gas: Highly superheated steam

Saturation: Synonym for phase equilibrium

Wet steam: Mixture of two phases in thermodynamic equilibrium

In the wet steam area there is always an explicit relationship between p and T, but the phases have different masses. (fig. 2)

Steam content x:

Index ' refers to the boiling fluid (on the boiling curve) and index " to the saturated steam on the dew curve. The following applies:  $m = m' + m''$  if m is the wet steam mass.

$$x = \frac{m''}{m' + m''}$$

$x = 0$  for boiling fluid (100% boiling fluid)

**$0 < x < 1$  in the wet steam area**

$x = 1$  for dry-saturated steam (100% dry-saturated steam)

Furthermore, the steam content is also a function of p and T in the wet steam area.

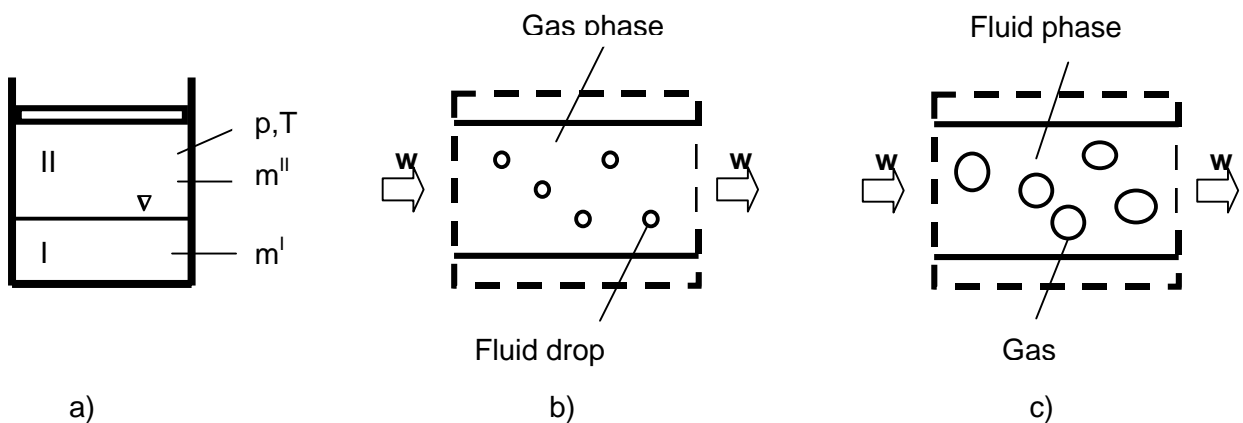


Figure 2: Phase equilibrium of a pure medium (wet steam)

For the thermodynamic idea of wet steam it is irrelevant whether both phases are expanded phases (case a) or if, in the case of flowed-through systems, the fluid phase is dispersed in the gas phase (case b) or the gas phase in the fluid phase (case c).

In all three cases both phases are in thermodynamic equilibrium and only differ in their masses.

(1)

If the droplets are in the  $\mu\text{m}$  area, the above mentioned approach no longer applies since the thermodynamic energy contents of the boundary surfaces also have to be taken into consideration.

## Thermodynamic processes during steam sub-cooling

As can be seen from the wet steam area in the p-v diagram in fig. 3 the saturated steam states (100 % dry-saturated steam, i.e.  $x=1$ ) are on the dew curve. Each pressure has a specific saturated steam temperature. In the wet steam area the isobars and isotherms coincide. They run as horizontal straight lines (states  $p_1, T_1$  or  $p_2, T_2$ ). If dry-saturated steam is cooled down in point 1, the wet steam area is approached according to the cooling level until the corresponding isotherm or isobar below is cut. A transition of point 1 to point 2 is given as an example. This new state in point 2 has a lower steam content ( $x < 1$ ). It is defined by a fluid portion  $(1-x)$  and a steam portion  $x$ . Both phases are in thermodynamic equilibrium.

The described processes are equilibrium considerations which are only valid for very slow processes.

If the fluid falls only slightly below the saturated steam temperature, the equilibrium is already metastable. Water does not yet condensate.

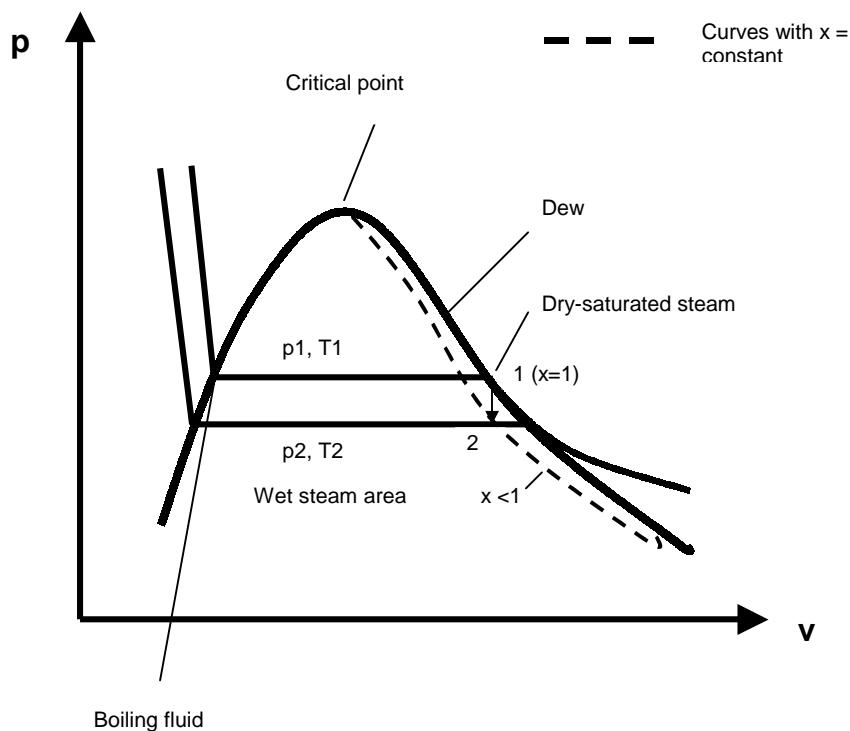


Figure 3: State change during cooling

## Condensation processes in steam lines

After representing the thermodynamic processes, the dynamic influences of the flow are explained below. Here it is important to know which factors initiate a phase transition and in which form the condensate can occur in the steam line.

Generally, three process change types can be distinguished during cooling processes (2):

- No phase transition occurs during quick cooling.  
The fluid state is in the metastable area (irrelevant for the further approach).
- Condensate occurs as a continuous phase on the pipe walls
- Condensate occurs as aerosol (fine mist droplets) in the steam flow

In practice especially the dynamic processes during steam measurements near the saturated state drastically change the steam state in the pipeline.

Depending on the flow or the steam rate, different forms of condensation develop along the pipeline due to heat losses (3):

Additionally, condensation can also develop within the steam flow.

### Condensation due to heat losses along the pipeline

Condensation within a horizontal pipe serves as example here. For this, it is assumed that heat losses along the pipeline can lead to different forms of condensate as shown in fig. 4. This reflects real conditions as they occur during practical saturated steam measurements.

Due to gravitational influences the condensate tries to collect in the base of horizontal pipelines resulting in the development of unsymmetrical forms of flow. (fig. 4)

Especially with small rates an unsymmetrical annular flow develops in the pipeline. In the gravity-controlled area the condensate in the pipe's base which has developed on the side walls and in the apex of the pipe drains off in the form of wave or layer flows. This form of flow remains in the sub-cooling zone without the development of further condensate in the top part of the pipe.

In the case of high steam mass flows, a slug flow and in the further condensation process a plug flow can quickly occur. These can develop into a single-phase flow in the sub-cooling zone.

Since condensation processes in vertical pipelines are quite similar, only the respective sources are referred to here. (VDI Heat Atlas, 6th Edition 1991)

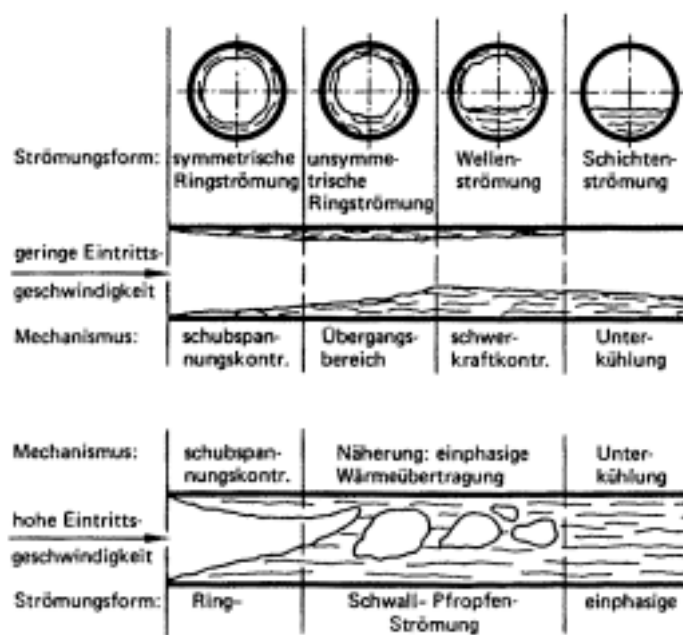


Figure 4: Flow forms in the case of condensation in a horizontal pipe

### Condensation due to steam impurities

Besides the condensation forms described above, condensation can also develop within the **steam flow** if a slight sub-cooling of the steam has been achieved. For this, the finest impurities in the form of foreign particles are used as a catalyst; they act as condensation germs and accelerate the condensation process.

The 2-phase flow of dry-saturated steam and boiling fluid resulting from the condensation processes described above can only be described **qualitatively** in the wet steam area. Quantitative statements about the state of the condensate and therefore about the composition of the flow in the wet steam area are not possible due to numerous influential factors and linked complexity.

An example helps to describe this.

### **Influence of density and differential pressure on the mass flow**

The wet steam area is limited by the boiling curve on the condensate side and by the dew curve (saturated steam curve) on the steam side. For this example, two defined states are observed at the same mass flow (5 t/h) and pressure differential device (standard orifice plate DN 100,  $d_i = 61.7$  mm).

1. Boiling fluid (100% condensate)  
Given:  
Mass flow: 5 t/h  
Temperature: 179.8 °C  
Pressure: 10 bar abs,  
Density: **887 kg/m<sup>3</sup>**  
**Req. effective pressure: 3 mbar**
2. Dry-saturated steam (100% saturated steam)  
Given:  
Mass flow: 5 t/h  
Temperature: 179.8 °C  
Pressure: 10 bar abs,  
Density: **5.15 kg/m<sup>3</sup>**  
**Req. effective pressure: 500 mbar**

This example displays the large differential pressure bandwidth between the boiling fluid (100% condensate) and dry-saturated steam (100% steam) caused by the respective density changes.

If the steam state is in the wet steam area due to the pressure and temperature conditions, a differential pressure is measured at the pressure differential device. Due to the relationships described above it is not possible to allocate a definite density to this measured differential pressure since the **density in the wet steam area cannot be determined**. Therefore, the flow determined from the differential pressure and density is **not plausible**.

## Conclusion

In the case of saturated steam measurements it should always be observed that the steam state is at least dry-saturated, if not even slightly superheated. Steam measurements in the wet steam area always lead to vague statements since there is a multitude of disturbance variables which cannot be determined but have a substantial impact on the density of the wet steam and thus also on the differential pressure.

Therefore, these operating states should always be avoided via respective measures.

## Measures

Measures for a reliable saturated steam measurement already start in the measurement planning phase. The following questions arise here:

- What are the requirements for the pressure, temperature and measuring range?
- What is the diameter of the (planned) pipeline?
- Is the pressure differential device installed in a horizontal or vertical pipeline?
- What is the flow direction?
- Is the straight inlet and outlet section sufficient?
- Is it possible to install steam traps in front of the measuring point?
- Is it possible to install a steam trap?
- Is a concentric reduction of the nominal diameter possible for lowering the pressure and improving the flow profile?

The answers to these questions result in the selection of an appropriate pressure differential device (e.g.: orifice plate, nozzle, venturi tube) for the respective measuring task.

This way, it is already possible to optimise the saturated steam measurement from the flow-technical side during the planning phase.

Here, it has to be observed that the state of the steam at the measuring point is at least dry-saturated (saturated steam). How can this operating state be maintained or checked? In the case of saturated steam measurements it should generally be observed that the temperature as well as the pressure of the steam is continuously recorded. In contrast to pure temperature-guided measurements, this requires high investment costs due to the additional pressure transmitter but has clear measuring advantages. A steam calculator calculates the state of the steam from the measured values for pressure and temperature. Therefore it can easily be determined whether the wet steam area has been reached. An error message signals this undesired operating state to the operator.

An error memory detects the duration of the pending fault. If the steam calculator is additionally equipped with a separate fault counter, the undefined steam volume is added up in the counter for the time period of the fault.

These possibilities clearly increase the quality of saturated steam measurements and provide the operators with important information about the actual steam state in their system.

## Device-related design of a METRA saturated steam measurement

### Differential pressure

**device:** Orifice plate, nozzle, venturi tube, PN16-PN160, DN15-DN500  
taking the on-site installation conditions into consideration

### Pressure

**transmitter:** DT 311(312) measuring range: 0 – 600 (2500 mbar)  
Overload-proof up to 80 bar one-sided  
Highest measuring accuracy and long-term stability due to hydraulic zero-balancing  
With integrated pressure sensor for recording the static pressure

**Calculation unit:** EBR 101 EZ with LCD multifunctional display for all relevant values, operation as steam energy or steam flow calculator  
operation and measurement hour meter,  
error analysis and memory, fault counters  
automatic correction of the flow coefficient and expansion number  
automatic correction of the temperature-dependent expansion of the pipeline and pressure differential device,  
analogue and relay outputs  
incl. the respective temperature sensor

**Calibration:** The entire measuring system can be calibrated on accredited test benches.

*Author: Rainer Hohenhaus  
METRA Energie-Messtechnik GmbH  
November 2002*

### Bibliography:

- (1) Institut für Technische Thermodynamik und Kältetechnik, Universität Karlsruhe TH, Germany*
- (2) Dipl. Ing. Fr. Mall-Gleißle ITTK, Universität Karlsruhe TH, Germany*
- (3) VDI Heat Atlas 6th Edition 1991*