Investigation of Steam Quality (Dryness Fraction)
Instrumentation

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Steam quality, also known as dryness fraction of steam, has considerable effects on performance of steam processes thus accurate knowledge of steam quality during a process is beneficial to the user. This report discusses findings of an investigation of steam quality instrumentation options appropriate for small scale steam power plant application. Conventional methods, such as calorimetry, require removal of a sample to be tested, which brings about difficulty ensuring the sample remains a true representation of the process steam. Tuneable Diode Laser Absorbance Spectroscopy is a promising alternative to conventional methods, which does not require sampling.

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Nomenclature
TDLAS = Tuneable Diode Laser Absorption Spectroscopy
IR = Infra-Red
HITRAN = High Resolution Transmission database

Equation Variables
\[ H \] = Total heat of 1kg if steam at boiler pressure (kJ)
\[ \Delta h_{\text{vap}} \] = Enthalpy of vaporisation at boiler pressure (kJ/kg)
\[ h_{\text{throttled}} \] = Total heat of steam after throttling (kJ)
\[ \Delta T \] = Difference in temperature due to throttling (K)
\[ C \] = Specific heat of the super-heated steam (kJ/K)
\[ X, x \] = Fraction by mass of liquid/gas in liquid-gas mixture (%)
I. Investigation Scope

This investigation is conducted as part of the design requirements of *Steam Plant Design – Final Year Project* by Jason Noonan for Mr. Alan Fien\(^2\). The design of a small scale steam plant for use as a training aid by students of the School of Engineering and Information Technology. The scope of the investigation is to identify methods of measuring steam quality, any issues of accuracy associated with the methods, and recommend any alternatives. This investigation is not exhaustive and is intended to be an introductory enquiry to inform the customer of potential issues and solutions. Further research and design/development of an appropriate instrument may be considered as a final year project for future students.

II. Steam Quality

Steam quality, also known as the dryness fraction of steam, has considerable effect on the performance and longevity of steam processing plants. Steam quality refers to the percentage, by weight, of liquid water within a liquid-vapour mixture. The process of generating steam from liquid water is not instantaneous. There exists a region between saturated liquid state and saturated vapour state where water particles of either state co-exist. This region is known as the liquid-vapour region. The term dryness fraction illustrates the fact that a fluid of 100% steam quality has no liquid particles and is said to be dry, or saturated vapour. The bold, black, bell shaped curve in Figure 1 represents the boundary for the saturated states of water at relative pressures and enthalpy values. Saturated liquid being to the left of the curve, saturated vapour to the right of the curve, and a liquid-vapour mixture within the curve.

![logP-h diagram](image)

*Figure 1- Moller Diagram for Water[1]*

The term saturated is used with regard to the reaction of the fluid due to a change in heat energy stored within it. When a volume of water begins to vaporize the applied heat energy no longer contributes to increasing the temperature of the fluid. Instead it contributes to changing the state of the fluid from liquid to vapour. When all liquid particles are vaporized and the process of changing the state of the fluid is complete, the fluid is said to be saturated with heat. This implies any further application of heat energy will not improve the quality of the vapour. Further heat addition will contribute to further increase in temperature. The steam quality of the liquid-vapour

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mixture is represented in Figure 1 by thin black lines and a value between x=0 and x=1 with ‘x’ indicating steam quality and the value representing the fraction of the mixture that is vapour. x=0 being the saturated water line and x=1 being the saturated vapour line. Vapour which has been heated beyond the saturated vapour line is said to be superheated.

It is clear that vapour contains more enthalpy than liquid for a given pressure and temperature. It is advantageous to supply the heat engine with hot, superheated steam because the working fluid’s ability to do work – say expand against the piston or rotate a turbine – increases with an increase in enthalpy. As well as increasing the fluid’s ability to do work, another advantage of high quality steam is the reduction of moisture in the system which reduces the onset of corrosion. Also, less build-up of moisture at junctions, fittings, and low-points will reduce the possibility of water hammer, and restriction to flow due to decreased cross-sectional area of the pipe. Moisture in the working fluid may also cause lubrication issues within the engine, as water droplets may emulsify the lubricating oil within the cylinder. Liquid pools within the system will reduce the thermal efficiency of the plant. This loss of thermal efficiency is due to the introduction of water particles into the fluid at the interface between the working fluid and the liquid. Some energy loss will occur as energy is transferred to the liquid particles in an attempt to equalize the temperature between the liquid and the working fluid and also accelerate the particles to the velocity of the working fluid.

III. Measuring Steam Quality

In practice, measuring the quality of process steam is difficult. Conventional methods for measuring steam quality involve removing a sample from the process to be analysed. The process of removing a sample causes some systematic uncertainty in the measurement and continuity may also be questionable if strict adherence to a standard is not observed.

A. Sampling Process Steam

The difficulty in sampling a process fluid is the ability to remove a sample that is representational of the working fluid. Changes in flow velocity (speed and/or direction), pressure and temperature can all cause the properties of the sample to deviate from those of the working fluid. A representative sample includes all impurities in the working fluid. The sampling method must facilitate this requirement. The transport of the sample to the analysis site may also effect the representational integrity of the sample. As soon as the sample has left the flow it is external to the operating conditions of the plant. Energy may be lost through conduction with cooler pipes and radiation. This loss of energy may cause some vapour to condense and so create a misrepresentation of the working fluid.

The American Society for Testing and Materials (ASTM) International have standardised the means in which samples shall be extracted from a process steam flow with ASTM D1066-11 Standard Practice for Sampling Steam. The mentioned standard defines the term Isokinetic Sampling. Isokinetic sampling requires the flow of the sample fluid to be of the same velocity and direction (at the point of extraction) as the working fluid from which it is being extracted.

“When the sample is not extracted isokinetically the contaminants in the steam are not properly represented.”

The standard also makes recommendations regarding the position of sample points with relation to junctions, bends and fittings. Differences in laminar and turbulent flows are also accounted for within the standard. The standard is concerned with sampling steam, not only for measurement of quality but also of impurity (contamination). It is for this reason the standard includes recommendations with regard to condensing the sample, to produce a liquid solution which may then be analysed. Adherence to ASTM D1066-11 does not guarantee a representational sample. A better solution is to design an instrument that may measure the quality (and possibly purity) of the steam without the need to remove it from the process flow.
B. Throttle-Calorimetry

A conventional method of measuring steam quality is the process of throttle-calorimetry. A diagram of a throttle-calorimetry apparatus is provided at Figure 2. First, a sample is removed from the flow and its temperature measured. The sample is then throttled to atmospheric pressure which shall cause the vaporizing of any liquid present in the sample. The temperature of the throttled steam is then measured.

The change in temperature due to throttling saturated steam can be calculated and expected. If this change in temperature is less than that expected, some of the heat energy must have been used to vaporize any liquid within the mix. This process assumes no energy transfer between the sample and the environment. The throttling process is isenthalpic. The formula below is used to calculate the fraction of liquid within the pre-throttled sample:\[ x = \frac{H - h - C(\Delta T)}{\Delta h_{\text{vap}}} \]

Where:

- \( H \) = total heat of 1 kg of steam at boiler pressure
- \( \Delta h_{\text{vap}} \) = enthalpy of vaporisation at boiler pressure
- \( h_{\text{throttled}} \) = total heat of steam after throttling
- \( \Delta T \) = Difference in temperature due to throttling
- \( C \) = specific heat of the superheated steam

The steam quality value is then given by: \( X = 1 - x \)

C. Separating Calorimeter

A separating calorimeter, such as Figure 3, mechanically separates the liquid from the steam. Both fluids are then measured by various means to find their mass and a comparison is then made to determine the steam quality. The fundamental principle which separator calorimeters operate on is the difference in the fluids ability to change direction due to its densities at different states. A vapour more readily changes direction than a liquid, and so the liquid particles take a wider path and can be removed as simply as placing an orifice at a bend in a pipe. This principle is common place in the design of cyclonic vacuum cleaners and ram-air intakes for high-performance vehicles.

D. Error with Calorimetry

Losses due to heat transfer from the sample to the environment is a major source of systematic error. This can be countered by preheating the instrument and maintaining the temperature equal to that of the process temperature. Radiation will still cause some losses. By far the greatest cause of error lies with the sampling of the fluid as discussed in A. Sampling Process Steam above.
IV. Tuneable Diode Laser Absorption Spectroscopy (TDLAS)

Significant advantages exist for measurements of temperature, concentration and other gas parameters in real-world environments due to the development of TDLAS systems [3]. Tuneable semiconductor diode lasers are compact, rugged, cost effective, compatible with optical fibre transmission and simple to operate. The lasers are narrow-linewidth light sources whose wavelength can be tuned easily by changing the laser temperature and injection current. Room temperature operated diode lasers provide access to the near-IR region of the optical spectrum, generally between ~0.7 and 1.6μm [4]. Widespread use of diode lasers within the telecommunications industry ensures technological advancement, continued availability, and low costs. TDLAS systems are simple, rugged optical arrangements with no moving parts. They are wavelength agile and can provide quantitative, multi-parameter measurement with a single instrument. Rapid development in mid-IR sources and detectors will significantly expand applications [5].

A. Photon Absorption

Absorption occurs when light is passed through an absorption medium. The intensity of the light is diminished due to the consumption of photons for the excitement of the molecules, specifically causing their electrons to “jump” up to a higher energy level. This only occurs when the energy level (wavelength) of the light matches the energy required to raise the electron into a higher energy level as demonstrated by Figure 4. The tuneable characteristics of diode lasers make it possible to refine the incident wavelength to target individual species.

B. Beer-Lambert Relation

The transmission of a probe beam of light through a uniform absorbing medium follows the Beer-Lambert relation [4]:

\[ \tau_\nu = \frac{I(\nu)}{I_0(\nu)} = \exp[-k(\nu)L] \]

Where:
- \( \tau_\nu \) = the transmissivity at frequency \( \nu \)
- \( I_0(\nu) \) = the incident (initial) intensity of the probe beam
- \( I(\nu) \) = Intensity at frequency \( \nu \) after propagation through a length \( L \) of the absorbing medium
- \( k(\nu) \) = the spectral absorption coefficient.

The intensity of a probe beam experiences exponential decay when propagated through an absorbing medium.

The spectral absorption coefficient contains information relating to the temperature, concentration, and velocity of the fluid medium. The spectral absorption coefficient may be expressed as follows [4]:

\[ k(\nu) = P_{abs}S(T,\nu_0)\phi(\nu - \nu_0) \]

Where:
- \( P_{abs} \) = partial pressure of the absorbing species
- \( S(T,\nu_0) \) = Line-strength of the transition
- \( \phi(\nu - \nu_0) \) = the line-shape function
1. **Partial Pressure**

Partial pressure is a measure of the contribution a particular gas makes to the overall pressure of a gas-mixture of known volume and temperature. Dalton’s Law of Partial Pressure can be derived from the ideal gas law:

\[ PV = nRT \]
\[ n = n_1 + n_2 \]
\[ \therefore PV = (n_1 + n_2)RT \]
\[ \therefore P = \frac{n_1}{V}RT + \frac{n_2}{V}RT \]
\[ \therefore P = P_1 + P_2 \]

2. **Line-Strength**

The line-strength data for water is published by the Harvard-Smithsonian Centre for Astrophysics, in a database known as HITRAN (High Resolution Transmission). The data for water-vapour absorption bands within HITRAN are based on a temperature of 296 K [4]. Line strengths at other temperatures may be calculated from the function:

\[ S(T, \nu_0) = (T_0, \nu_0) \left( \frac{T}{T_0} \right) \left[ \frac{Q(T_0)}{Q(T)} \right] \]
\[ \times [1 - \exp\left(-hc\nu_0/kT\right)] \]
\[ \times [1 - \exp(-hc\nu_0/kT_0)]^{-1} \]
\[ \times \exp\left(\left(\frac{kE''}{k}(1/T - 1/T_0)\right)\right) \]

Where:

\[ T_0 = 296 \text{ K} \]
\[ h = 6.62606957 \times 10^{-34} \text{ m}^2\text{kg}/\text{s} \text{ (Planck's Constant)} \]
\[ k = 1.3806488 \times 10^{-23} \text{ m}^2\text{kg}/\text{s}^2\text{K} \text{ (Boltzmann Constant)} \]
\[ c = 299792458 \text{ m}/\text{s} \text{ (Speed of light)} \]
\[ \nu_0 = \text{resonant frequency of the line} \]
\[ E'' = \text{Lower state energy transition (m}^{-1}) \]
\[ Q(T) = \text{Rovibrational Partition Function} \]
\[ = 0.5\left[\frac{\pi}{ABC}\right](kT/hc)^3 \left( 0.5 \times [1 - \exp\left(-hc\nu_1/kT\right)]^{-1} \times [1 - \exp\left(-hc\nu_2/kT\right)]^{-1} \times [1 - \exp\left(-hc\nu_3/kT\right)]^{-1}\right) \]

Where:

\[ A, B, C = \text{rotational constants of an asymmetric top rotor for water as follows} \]
\[ A = 27 \text{ cm}^{-1} \]
\[ B = 14.4 \text{ cm}^{-1} \]
\[ C = 9.4 \text{ cm}^{-1} \]

\[ \nu_1, \nu_2, \nu_3 = \text{fundamental vibration frequencies} \]
\[ \nu_1 = 3657.05 \text{ cm}^{-1} \]
\[ \nu_2 = 1594.75 \text{ cm}^{-1} \]
\[ \nu_3 = 3755.93 \text{ cm}^{-1} \]
3. Line-Shape

The line-shape function may be expressed in terms of a Voigt profile characterised by the half-widths of the collision and Doppler broadening values. The profile may be represented by the following equation [4]:

\[
\alpha = (\ln 2)^{0.5} \frac{\gamma_c}{\gamma_D}
\]

Where \(\gamma_D\) and \(\gamma_c\) are the Doppler and collision half-widths respectively. The collision half-width is determined by experiment. The Doppler half-width is calculated by:

\[
\gamma_D = 3.581 \times 10^{-7} (T/M)
\]

Where:

\[ T = \text{temperature} \]
\[ M = \text{molecular weight of absorber} \]

4. Measuring Steam Quality

Once temperature, line-strength, and path length are known, the partial pressure shall be calculated from the two equations at B. Beer-Lambert Relation above [4]. Then, once total pressure is known, the mole fraction of water vapour shall be calculated with:

\[
X = \frac{P_{\text{abs}}}{P_{\text{total}}}
\]

C. Considerations of TDLAS

Whilst TDLAS negates the sampling requirement, line-of-sight, right-through access to the process steam is required. In order to pass the light through the steam, a sight-glass must be installed. On choosing the appropriate location for the sight-glass due consideration should be given to any possible reasons the flow may not be indicative of the delivery flow to the plant including distance from plant, bends, valves, traps, gauges, and any other assemblies which may vary the characteristics of the steam flow from that which is ultimately delivered to the plant. The sight-glass window shall be such that it neither hinders the operation of the instrument nor does it cause any changes to the flow of the steam. This includes allowing heat energy to escape via radiation through the window, and sharp edges internal to the pipe creating un-uniform flow.

Path-Averaging is a source of systematic error with TDLAS. The intensity shift of the light due to absorption is a result of collision with every particle in its path. The Beer-Lambert Relation is a differential equation, and the result is a mean value over the length of the path. One, single pass, path shall prove sufficient for small scale steam plant. Paths may be extended by the use of mirrors, or more lasers may be introduced in a regular pattern to produce a tomographic chart from which a more accurate result may be derived.

The fact that TDLAS systems use tuneable lasers provides options for future considerations such as targeting other species within the fluid to monitor contamination levels, for example. TDLAS systems have low energy requirements, are automated, and require far less volume than conventional sampling and calorimetry equipment.

V. Recommendation

TDLAS is recommended as the most suitable method of steam quality instrumentation for small scale steam plant owing to the availability of appropriate lasers, low energy requirement, small volume, and simple construction and operation. Removing the requirement to sample the steam is by far the most advantageous characteristic of TDLAS compared to conventional methods such as the calorimetry methods discussed. Installation of an appropriate TDLAS instrument on a small scale steam plant will contribute to the safe and efficient operation of the plant. Including the TDLAS system in the design stage of the plant is beneficial, ensuring the final design includes, or has scope for retro-fitting the system.
References


Other Texts Consulted

4. O‘byrne, Dr Sean, 2015 Absorption Talk, Power Point presentation, School of Engineering and Information Technology, University of New South Wales Canberra, 2015