Results Of A Computer Simulation Of A Nonintrusive, Optical Steam Quality Monitor

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Introduction

In a steam plant, the liquid phase cannot be completely eliminated from steam produced in the steam generator. As the steam travels from the boiler to the turbine, heat loss through the walls of the pipe causes condensation, producing additional liquid phase. Liquid phase in saturated steam is present in the form of small droplets. Water droplets traveling at high velocities impact on the turbine blades and pipe walls, causing erosion. This leads to eventual, and possibly catastrophic, mechanical failure of these components.

Wetness factor, or fraction of total mass in liquid phase, serves as an indication of plant efficiency and normal operation. During start-up, accidents, or anomalous plant operation, the wetness factor may reach high levels. Continually monitoring wetness factor would allow real time adjustment of plant parameters, improving plant efficiency and reducing maintenance.

A nonintrusive, continuous, optical steam quality monitor is proposed. A diagram of the proposed monitor is shown in Figure 1. Light from a laser source is injected into the steam flow and scattered by water droplets. Detectors are located at various angular positions around the pipe walls, and focused at a common point along the path illuminated by the source. Light scattered by the droplets is incident on the detectors, and the intensity of this scattered light is measured. The angular variation of scattered intensity can then be inverted to give the size-number density distribution of the droplets.

There are three significant advantages to the proposed monitor. First, since a probe is not used, measurements at high pressure can be made without using elaborate mechanical supports. Second, since there is no probe, the steam flow will not be disturbed. Finally, measurements can be made on a continuous basis, allowing immediate detection of anomalous conditions and long term measurements for improved diagnostic analysis.

There are also some disadvantages to the proposed monitor. Water may condense on the detectors, adversely effecting their performance. Also, multiple ports will be necessary for the detectors. However, devices will be mounted in the ports rather than inserted through the ports, requiring less equipment.

A FORTRAN computer program was written to simulate the operation of the monitor. The scattered light intensity incident on the detectors was determined using Mie theory.\(^1\)\(^2\)\(^3\) Extinction between the source, scattering volumes, and detectors was also determined. Simulations were performed at various wetness factors, light source frequencies, particle size-number density distributions and pressures. The results were analyzed to determine if the monitor could distinguish changes in wetness factor under various operating conditions.

Theory

The Deirmendjian distribution\(^4\) of droplets in an aerosol can be written as:

\[
N(a) = C a^2 e^{-\frac{a}{r_m}}
\]

(1)

where \(a = \frac{r}{r_m}\)

(2)

and \(r\) is the radius of a particle, \(r_m\) is the most probable radius of the particle, \(N(a)\) is the size-number density distribution of the particle, \(C\) is a normalizing constant, and \(\alpha\) and \(\gamma\) are parameters effecting the width and skew of the distribution, respectively.\(^5\) In this work, the application is to wet steam, a mixture of water droplets and water vapor. A relationship between steam quality and the size-number density distribution of the water droplets is required.

The wetness, or fraction of total mass in liquid phase, of the steam is defined as:

\[
W = \frac{m_f}{m_{f} + m_v}
\]

(3)

where \(W\) is the wetness, \(m_f\) is the mass of the liquid phase, and \(m_v\) is the mass of the vapor phase. This can be rewritten as:

\[
W = \frac{\rho_f V_f}{\rho_f V_f + \rho_v V_v}
\]

(4)

where \(\rho\) represents specific density and \(V\) represents volume. Solving for \(V_f\) gives:

\[
V_f = \frac{W \rho_f V_f}{\rho_f + W (\rho_v - \rho_f)}
\]

(5)
where $V_T$ represents total volume. If the wet steam is contained in a cylindrical volume of height $\ell$ and diameter $d$, and $r$ is the radius of the water droplets, then the total volume in liquid phase is:

$$V_T = \int_0^\ell \int_0^d \int_0^\infty N(f) \frac{4}{3} \pi r^2 \delta r \delta \ell$$  \hspace{1cm} (6)

Substituting

$$N(a) = N \left( \frac{r}{r_m} \right)$$ \hspace{1cm} (7)

and

$$\delta_r = r_m \delta_a$$ \hspace{1cm} (8)

and integrating over the volume of the cylinder gives:

$$V_T = \pi d^2 \ell \int_0^{r_m} \int_0^\ell \int_0^\infty N(a) \frac{4}{3} \pi r^2 \delta a$$ \hspace{1cm} (9)

Substituting Equation (1) into Equation (9) gives:

$$V_T = \pi d^2 \ell \int_0^{r_m} \int_0^\ell \int_0^\infty \frac{4}{3} \pi r^3 N(a) e^{-\frac{a}{a'}} a^3 \delta a$$ \hspace{1cm} (10)

Combining Equations (5) and (10) and solving for $C$ yields:

$$C = \frac{W_{rho}}{r_2 \pi r_m^4 \int_0^{r_2} a^2 e^{-\frac{a}{a'}} a^3 e^{-\frac{a}{a'}} a^3 \delta a}$$ \hspace{1cm} (11)

where $r_1$ and $r_2$ are the minimum and maximum values of the particle radius, respectively. The above equations can also be solved for the steam wetness:

$$W = \frac{\rho_T}{(\rho_T - \rho_v) + \frac{\rho_v}{\rho_T}}$$ \hspace{1cm} (12)

where

$$X = \frac{4}{3} \pi r_m^3 C \int_0^{r_1} a^2 e^{-\frac{a}{a'}} a^3 e^{-\frac{a}{a'}} a^3 \delta a$$ \hspace{1cm} (13)

The specific densities depend on the temperature and pressure of the steam. If the size-number density distribution, represented by $X$, is determined experimentally, the wetness can be easily determined. Quality is the fraction of total mass in vapor phase. Using $Q$ for quality and $W$ for wetness, quality is given by:

$$Q = 1 - W$$ \hspace{1cm} (14)

Results

Input data were selected to represent two points in a steam generator, the input to the high pressure turbine and the output from the low pressure turbine. At high pressure, the steam was assumed to be saturated at 40 bars. The size-number density distribution was assumed to range from 0.1 to 100 microns, to have its maximum at 1 micron, and to decrease by one order of magnitude from its maximum to its extremes. At low pressure, the steam was assumed to be saturated at 38 mbars. The size-number density distribution was assumed to range from 0.1 to 10 microns, to be maximum at 1 micron, and to decrease by five orders of magnitude from its maximum to its extremes. In both cases, saturated steam was assumed to be flowing through a pipe one meter in diameter, the source was assumed to be a laser with an intensity of $1 W/m^2$ and a beam diameter of 1 mm, and the water droplets were assumed to have a dielectric constant $m = 1.33$ for all wavelengths.

The simulated monitor was assumed to have detectors at detector angles of 10°, 45°, 90°, 135°, and 170°, and a source at source offset angles of either 0°, 60°, or 75°. The detector angle is the angle between the detector and the forward direction of the illuminated path measured at the midpoint of the illuminated path. The offset angle of the source is the angle between the source and a horizontal line through the center of the pipe measured from the center of the pipe.

The detectors were assumed to be focused on the midpoint of the illuminated path, and to have acceptance angles of 10°, which are typical of optical fibers. Smaller acceptance angles are possible with the use of optics.

Figure 2 shows intensity versus detector angle for wetness factors of 5.0, 1.0, and 10 percent, 0° offset angle, and incident wavelength of 488 nm at low pressure. Figure 3 shows intensity versus detector angle for wetness factors of 5.0, 1.0, and 10.0 percent, 60° offset angle, and 488 nm incident wavelength at low pressure. Maximum intensities occur in the forward and backward direction, while the minimum occurs at an angle perpendicular to the path of the incident light. Intensities decrease as wetness factor decreases for all values of detector angle.

Figure 4 shows relative intensity versus wetness factor at low pressure. Relative intensity is defined as the ratio of intensity at a given wetness factor and detector angle to intensity at a wetness factor of 1 percent for the same detector angle. These ratios were found to be independent of detector angle, frequency, or offset angle. Relative intensity is a nearly linear function of steam quality for a given size-number density distribution. Intensity depends on the number of water droplets in the steam. The number of water droplets depends on the constant $C$ in the Deirmendjian distribution. For a given size-number density distribution, this constant is a weak function of wetness, and is approximately equal to a constant times wetness factor. Therefore, intensity should be approximately equal to a constant times wetness factor for a given size-number density distribution.

Figure 5 shows intensity versus detector angle for wetness factors of 1.0, 0.5, and 0.1 percent, with an offset angle of 0° and incident wavelength of 488 nm at high pressure. As with low pressure, intensity increases as the percent of steam in the liquid phase increases for all values of detector angle. Relative intensity was found to be a nearly linear function of steam quality for a given size-number density distribution at high pressure as well.
Conclusions

The purpose of this study was to determine the feasibility of the proposed monitor by simulating its operation with a computer program. In particular, the intensity of scattered light received by the detectors, and variations of the intensity with changes in wetness, were determined. Various implementations of the monitor were simulated at both high and low pressure. The ratio of steam qualities was found to be nearly linear for a given size-number density distribution.

References
Figure 4. Relative intensity versus wetness factor at low pressure.

Figure 5. Intensity (W/m²) versus detector angle for (1) 0.5%, (2) 0.2%, (3) 1.0% wetness factor, 0° offset angle, and 488 nm incident wavelength at high pressure.