Feedback dew-point sensor utilizing optimally cut plastic optical fibres

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Abstract. A plastic optical fibre reflectance sensor that makes full use of the critical angle of the fibres is implemented to monitor dew formation on a Peltier-cooled reflector surface. The optical configuration permits isolation of optoelectronic components from the sensing head and better light coupling between the reflector and the detecting fibre, giving a better signal of the onset of dew formation on the reflector. Continuous monitoring of the rate of change in reflectance as well as the absolute reflectance signals, the use of a novel polymethyl-methacrylate-coated hydrophobic film reflector on the Peltier element and the application of feedback around the point of dew formation, further reduces the possibility of contamination of the sensor head. Under closed-loop operation, the sensor is capable of cycling around the point of dew formation at a frequency of 2.5 Hz.

Keywords: dew-point sensor, humidity, plastic optical fibres, intensity referencing

1. Introduction

Typical dew-point sensors consist of a mirror cooled by a small Peltier unit. The current fed to the cooler is adjusted until dew begins to form on the mirror; this is detected by a capacitive [1] or optical [2] sensor. The temperature of the mirror surface is then measured by a suitable temperature transducer. The condensation dew-point hygrometer is used by almost all laboratories as the reference instrument for the calibration of other types of hygrometers and is widely believed to be the key instrument for the foreseeable future [3].

Generally, the instruments used by standards laboratories are fitted with microscopes [4] to enable the condensate to be inspected. However, most commercial condensation hygrometers are not fitted with a microscope and they rely on the original calibration. The major limitations of such systems are the tendency for the mirror to become contaminated by aerosol particles, which shifts the condensation point to higher temperatures, and the relatively slow time response of the system. Some systems include detection and correction circuits that eliminate the effect of optical contamination using an optical balance (Model Dew 10, General Eastern Co., USA). The problem of slow time response can be partially reduced by using a cyclic cooling system [5], consisting of a first stage where the mirror is rapidly cooled to approximately 1.5 °C above the last known dew point, a second stage in which a slow cooling rate is applied until dew formation is detected, a third reheat stage and a final wait stage. This technique, however, is not always effective as no information regarding the onset of dew is used to continuously adjust the direction of current in the Peltier element as would be the case in a true feedback system.

Furthermore, in many industrial applications the sensor must be capable of measuring dew points in environments where the air might be static and hot. A standard method of isolating the opto-electronic components from the sensing head has been the use of a bifurcated fibre-optic cable with a random distribution of emitting and receiving glass fibres (Protimeter Inc., UK). In order to improve the efficiency of the transmitting and receiving fibres and to cover a larger detector area, many thin optical fibres must be used. An alternative technique is therefore proposed for sensing dew formation using plastic polymethyl methacrylate (PMMA) 1 mm fibres.

The system described here employs a novel optical fibre method for detecting the formation of dew and a feedback circuit to control the temperature of a PMMA-coated hydrophobic thin-film reflector in a narrow range around the dew point. These features improve the response time of the sensor and minimize the long-term drifts due to reflector contamination which are typical for this type of sensor. In contrast to an earlier version of the sensor [6], where the feedback system utilized only a reference reflectance setting and proportional control, the incorporation of derivative control further reduced the response time of the system and minimized the amount of dew formed on the reflector.

2. Optical configurations

The dew detection sensor utilizes a novel dual optical fibre reflectance probe. Calculations using the Fresnel equations...
show that the reflection coefficient of dew formed on the reflector is a function of incident angle, and it is therefore beneficial to emit and receive light at an angle with respect to the vertical of the reflector. A simple configuration that achieves this requirement involves cutting the emitter (TX) and receiver (RX) fibres at an optimal angle (α), to make full use of the critical angle of the fibre (figure 1). This ensures improved coupling and therefore a better signal-to-noise ratio. The condition for optimal α occurs when the ray emerging from the fibre, at the most acute angle, is parallel to its sloping face: using Snell’s law to cut the fibres gives \( n_{\text{air}} \sin 90^\circ = n_{\text{core}} \sin (18.2^\circ + \alpha) \), where \( n_{\text{core}} \) is the refractive index of the fibre and \( \alpha = 23.8^\circ \). However, a significant improvement in performance is obtained by cutting the fibres twice [7], at angles of 24° and 66°, as shown in figure 2. The double-cut fibres are essentially repositioned single-cut fibres so that their cut face is perpendicular to the reflector. The second cut, which is made along the fibre axis, improves the amount of reflected light received by the receiving fibre due to its closer proximity to the reflecting surface. The sensor starts responding once the size of the dew formed on the reflector becomes similar to the wavelength of light. Using a thin opaque film (paint) between the two fibres eliminates light directly coupled from the emitter to the receiver in the double-cut configuration, which would otherwise increase the standing noise at the photodetector.

The response of the transducer is proportional to the optical power entering the receiving fibre and can be analysed as a flux transfer problem. For a perfect reflector, the receiving fibre can be considered as facing the emitting fibre at a distance that between the emitter fibre tip and the reflector (figure 3). The face of the cut fibre has an elliptical shape, with minor axis the fibre radius \( r_1 \) and major axis \( r'_1 = r_1 / \cos(\alpha) \). The ray inside the emitting fibre, incident on the cut surface at an angle \( \theta \), will exit at an angle given by the refraction condition \( B(\theta) = \sin^{-1}(n_{\text{core}} \sin \theta) \) according to Snell’s law, with \( n_{\text{air}} \) taken as 1.

\[
\Phi = \int_A \int_{\Delta a} \frac{L' \cos \theta' \cos \psi}{R^2} \, ds \, da
\]

where \( L' \) is the radiance function at the surface of the transmitting fibre, \( \theta' \) is the exit angle of the ray from the transmitting surface, \( R \) is the range of the receiving point in relation to the transmitting point, and \( \psi \) is the angle of incidence of the ray on the receiving surface which is, in fact, equal to the exit angle \( \theta' \) from the transmitting surface since the two surfaces are parallel. A similar observation can be made for the azimuth of the ray from the transmitter surface, so that \( \phi = \omega \). The radiance \( L' \) is derived from the function \( L \) evaluated at the position of the source area element \( ds \) and at a direction \( (\theta, \phi) \), such that \( B(\theta) = \theta' \) and \( \theta' \) and \( \phi \) are calculated from the relative positions of the transmitting and receiving surface elements, \( ds \) and \( da \).

Calculations of the flux incident on the receiving fibre are performed in two stages: firstly, starting from the emitting fibre calculating the flux reaching the reflector, and then starting from the reflector, whose scattering function changes according to the amount of dew formed, and calculating the flux reaching the receiving fibre. Calculations are performed at an optimal distance \( d_{\text{opt}} \) from the emitting and receiving fibres. Integration is performed at a fixed distance where \( \frac{d\Phi}{d\theta} |_{d=d_{\text{opt}}} = 0 \) for all the points on the reflector and all the points on the receiving fibre after taking into account
an attenuation function \( \zeta(\theta, \phi, r, k) \), which is related to the amount of dew formed on its surface:

\[
\zeta(\theta, \phi, r, k) = \frac{1}{k r^2} F(\theta, \phi)
\]

(2)

where \( F(\theta, \phi) = \sum_i f_i(\theta, \phi) \), i.e. the sum of scattering functions of individual particles, and \( k = 2\pi/\lambda \) is the wavenumber.

In figure 3 we first assume a point source \( P \) on the emitting cut fibre with coordinates \( P = (x_e, y_e, 0) \). A point \( Q \) at position \( (x_a, y_a) \) relative to the position of the centre of the receiving surface will have coordinates \( Q = (x_a, y_a, h(d)) \) and \( h(d) = 2d \). The distance \( R \) can be calculated from

\[
R(x_s, y_s, x_a, y_a, d_{opt}) = |PQ| = \sqrt{(x_a - x_e)^2 + (y_a - y_e)^2 + h^2}.
\]

(3)

The angles \( \theta' \) and \( \phi \) are calculated from

\[
\theta'(x_s, y_s, x_a, y_a, d_{opt}) = \cos^{-1}\left( \frac{2d_{opt}}{R(x_s, y_s, x_a, y_a, d)} \right)
\]

(4)

and

\[
\phi(x_s, y_s, x_a, y_a) = \tan^{-1}\left( \frac{y_a - y_e}{x_a - x_e} \right).
\]

(5)

In order to calculate \( \theta \) we can use \( B^{-1}(\theta') = \theta \) so that \( \theta = \sin^{-1}(\frac{d_{opt}}{R}) \). The flux on the receiving fibre is, therefore,

\[
\Phi(d_{opt}) = \int_{-r_1}^{r_1} \int_{-r_1}^{r_1} \int_{-r_1}^{0} \zeta(\theta, \phi, r, k) \times \frac{L(x_s, y_s, \theta, \phi) \cos^2 \theta'}{R(x_s, y_s, x_a, y_a, d_{opt})} \, dx_s \, dy_s \, dx_a \, dy_a.
\]

(6)

The amount of flux on the receiving fibre is first converted into a photocurrent and then into a voltage via the transimpedance amplifier. The resulting signal, after being modified by the characteristics of the phase-sensitive detector (PSD) and amplifier, the resulting signal, after being modified by a photocurrent and then into a voltage via the transimpedance amplifier. The resulting signal, after being modified by the characteristics of the phase-sensitive detector (PSD) and amplifier, constitutes a part of the overall sensor transfer function.

The sensitivity of the system to changes in the forward path is related to the stabilization of the emitter, shown in figure 4, can be calculated (figures 5(a) and (b)) after taking into account the optical coupling of the system. It can be seen that the phase margin of the loop is 60° and the gain margin is 26 dB. Although the phase margin is relatively small, the system is stable. However, if a larger phase margin was to be incorporated into the design, so that the risk of drifts in the op-amps leading to a zero-phase margin would be eliminated, the lag–lead compensator could be modified. The large gain in the forward path (70 dB) results in a very stable emittance of the LED. Defining the system sensitivity as the ratio of the percentage change in the system transfer function \( Q \), the sensitivity \( S \) becomes

\[
S = \frac{\Delta Q/Q}{\Delta A/A} \approx \frac{\partial Q}{\partial \ln A}.
\]

(10)

The sensitivity of the system to changes in the forward path \( A \) is

\[
S_A^Q = \frac{1}{(1 + AB)^2} A/(1 + AB) = 0.104 \times 10^{-3}
\]

(11)

3. Feedback scheme for the stabilization of the emitter

A feedback circuit that thermally stabilizes the LED light source is also incorporated into the design. Amplitude modulation, intensity referencing and phase sensitive detection are used to minimize environmental noise. The forward path of the circuit comprises a differential amplifier, a high-gain amplification stage and a voltage-to-current converter (\( V-I \)). The feedback path contains a photodiode (\( R_{cell} \)), a current-to-voltage converter (\( I-V \)), a PSD with low-pass filtering, and a compensator. A detailed description of the circuit used can be found in [9].

When applying negative feedback, for high loop gains, the system response is governed by the characteristics of the feedback path \( B \). Therefore, for a very linear feedback characteristic, the nonlinearities in the forward path \( A \) will be reduced by (1 + loop gain), and using transfer function notation for figure 4:

\[
Q = \frac{x}{REF1} = \frac{A}{1 + AB} \approx \frac{1}{B}.
\]

(7)

Using the closed-loop configuration, the response of the voltage-to-current converter supplying the current in the LED is not critical for good thermal stability. In contrast, the two receivers with the corresponding PSD and filter must be matched as closely as possible if a unity gain of the overall system is desirable. Such a scheme ensures that the observed output is a function of the target reflectance and therefore the flux on the receiving fibre shown in equation (6), as well as the reference voltage:

\[
Q = \frac{OUTPUT}{REF1} = \frac{A}{1 + AB} \approx \frac{1}{B}.
\]

(8)

\[
\therefore OUTPUT \approx \frac{1}{B}REF1.
\]

(9)

The gain and phase Bode plots of the overall loop that is related to the stabilization of the emitter, shown in figure 4, can be calculated (figures 5(a) and (b)) after taking into account the optical coupling of the system. It can be seen that the phase margin of the loop is 60° and the gain margin is 26 dB. Although the phase margin is relatively small, the system is stable. However, if a larger phase margin was to be incorporated into the design, so that the risk of drifts in the op-amps leading to a zero-phase margin would be eliminated, the lag–lead compensator could be modified. The large gain in the forward path (70 dB) results in a very stable emittance of the LED. Defining the system sensitivity as the ratio of the percentage change in the system transfer function \( Q \), the sensitivity \( S \) becomes

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\]

(11)
and the sensitivity of the system to changes in the feedback element is

\[
S^Q_B = \left[ \frac{A}{1 + AB} \right]^2 \frac{-B}{A/(1 + AB)} = \frac{-AB}{1 + AB} = -1. \quad (12)
\]

Finally, in order to further improve the performance of the overall circuit with respect to noise, the bias voltage from the transimpedance amplifier in the forward path (corresponding to the standing current \( \Im I_a \) at the midpoint of the linear region of the operational range of the transducer), must be matched with the standing noise current \( I_b \) from the transimpedance amplifier in the feedback path using a custom-made optical coupler. The design of the optical coupler therefore requires that \( I_b = \Im I_a + I_b \) and \( I_a = I_b \), so that \( I_b = \frac{1}{1 + \Im} \). Such a requirement can easily be met by the double-cut configuration which has a small stand-off distance from the reflector.

It is well known [10] that the optical power distribution among the modes of a multimode fibre depends on the light injection conditions and on the coupling between the modes taking place along the fibre, due to core or core-cladding irregularities emanating from bends and microbends. Such variations could seriously compromise the performance of the intensity referencing scheme used, especially if they were to occur in the feedback component of the control loop. The sensitivity of the system to such variations could easily
Figure 6. Electronic diagram showing the feedback circuitry for the Peltier element.
be calculated by incorporating an extra term in equations (11) and (12). Fluctuations of the power distribution among the modes could be minimized by incorporating a mode scrambler in the design, even though these are not, to the author’s knowledge, commercially available for plastic fibres.

4. Peltier feedback circuit design

In order to implement feedback around the point of dew formation, the dc signal from the optical fibres after the PSD and filter is used. The smaller rms variation in reflectance (shown in table 1) for the double-cut configuration and the improved light coupling permit differentiation of the reflectance signal. This is achieved by slightly modifying the circuit shown in figure 6 by introducing a lead–lag circuit after the PSD and filter. Such a circuit differentiates the reflectance signal and provides low-pass filtering for the higher frequencies amplified by the differentiator. A combination of the reflectance signal and of the point of inflexion of the rate of change of dew is therefore used to set the input signal in the comparators CM1 and CM2.

In order to avoid any undesirable offset from the output of the differentiator, its positive input is adjusted through the output of the 1 K variable resistor. The references of CM1 and CM2 (40 mV hysteresis) are also adjusted to change simultaneously through a 10 K variable resistor providing a constant difference of 200 mV. The function of CM1 is to trigger at the positive slope of the differentiated signal, while CM2 triggers at the negative slope.

The output from CM1 passes through NOR gate 1 and is used to set the output Q of a CMOS 4013 flip-flop which provides the signal for the Peltier driving circuit. The other input of the NOR gate is connected to the output of the comparator CM3. Its function is to compare the temperature of the reflector with the ambient temperature and provide a reset function to the flip-flop if the difference in temperature between the two is larger than a set value. This ensures that in the event of the feedback system missing the dew point and being in a continuous cooling mode, it will reset itself after a threshold reflector temperature. Similarly, the output from CM2 passes through NOR gate 2 and resets the output of the flip-flop. The function of CM4 is similar to the function of CM3, the only difference being that it triggers when the temperature of the reflector is above a certain value from ambient. The feedback signals from CM3 and CM4, however, are rarely used due to the improved detectivity of the onset of dew in the double-cut configuration. The ambient temperature and the temperature of the reflector are sensed using thin, rapid-response-time thermocouples connected to monolithic thermocouple amplifiers (AD595) with cold junction compensation.

The output from the flip-flop is used to drive the two transistors TR1 and TR2. The configuration ensures that there are three distinct stages in their operation during a single duty cycle. When TR1 is low (0 V) TR2 is high (10 V), when TR1 is low TR2 is low, and finally, when TR1 is high TR2 is low. The operation ensures that no short-circuit in the Peltier current passing through the MOSFETs occurs during switching. At the first stage MOSFETs 1 and 3 are ON while 2 and 4 are OFF. For a very short time all MOSFETs are OFF. Finally, MOSFETs 1 and 3 are OFF while 2 and 4 are ON, thus reversing the current in the Peltier. A complete cycle implements a bang–bang controller operating around the point of dew formation on the reflector.

5. Application of feedback around the point of dew formation

In order to continuously operate around the point of dew formation, a feedback loop was designed to make the reflector temperature $T_{\text{mir}}$ track the temperature at which dew is formed $T_{\text{dew}}$. Once the sensor is switched on, the reflector temperature $T_{\text{mir}}$ starts from an ambient temperature $T_{\text{amb}}$ and tries to follow the dew-point temperature $T_{\text{dew}}$. The difference between $T_{\text{dew}}$ and $T_{\text{mir}}$ results in a loss in reflectance on the reflector, reducing its original reflectance. Initially, the system may be assumed to be described by the general diagram shown in figure 7(a). The fibre-optic configuration is adjusted for maximum reflectance (by optimizing its distance from the reflector as described in section 2), so that the maximum reduction in reflectance is observed due to the dew formation process. The observed flux of the reflected light depends on the absolute reflectance of the surface, the fibre-optic configuration used and the amount of dew formed on the reflector. The sensor produces a voltage proportional to the reflected light. The sensor transfer function STF gives the relation between reflectance and voltage. Ensuring that the sensor operates just below the point of dew formation allows us to perform a small signal analysis of the STF, ignoring the pure time delay describing the actual process of dew formation on the reflector when its temperature is below $T_{\text{dew}}$, and approximating the STF by a gain $dV/dT$ plus an offset $V_{\text{off}}$, as shown in figure 7(b). The validity of such an approximation is shown in figure 8 where the slope and offset have been measured for $T_{\text{dew}} = 12^\circ\text{C}$ under closed-loop conditions by simply adjusting the reflectance using $V_{\text{ref2}}$ resulting in a slope of $-2.4 \times 10^{-3}$ V grad$^{-1}$, and an offset of 1.21 V.

Table 1. Collective results of theoretical rms variation in reflectance arising from the total noise in the photodiode, fibre stand-off distance, duty cycle frequency and reflector surface temperature variation, for the three sensor configurations using proportional control. Results shown are for the ECP-305 reflector.

<table>
<thead>
<tr>
<th>Sensor type (%)</th>
<th>Rms variation in reflectance (%)</th>
<th>Stand-off distance (m)</th>
<th>Duty cycle (Hz)</th>
<th>Reflector temperature variation $\Delta^\circ\text{C}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Uncut (90°) fibres</td>
<td>$8.300 \times 10^{-6}$</td>
<td>$1800 \times 10^{-6}$</td>
<td>0.26</td>
<td>5</td>
</tr>
<tr>
<td>Single-cut (24°) fibres</td>
<td>$3.964 \times 10^{-6}$</td>
<td>$1200 \times 10^{-6}$</td>
<td>0.45</td>
<td>0.1</td>
</tr>
<tr>
<td>Double-cut (24°, 66°) fibres</td>
<td>$2.841 \times 10^{-6}$</td>
<td>$400 \times 10^{-6}$</td>
<td>0.58</td>
<td>0.1</td>
</tr>
</tbody>
</table>

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The low-pass filter which is used at the sensor output ensures that no high-frequency noise components are present in the signal. The resulting voltage signal passes through a proportional plus derivative ($K_p + sP_d$) controller whose gains are to be adjusted for the optimal operation of the system. The largest possible loop gain ensures the stability of the system, whereas increasing the gain of the derivative controller improves the system’s response time at the expense of the system stability (the high-pass characteristic of the controller amplifies the high frequencies present in the error signal $T_{\text{error}}$ as well as any electronic noise emanating from the sensor).

The signal is then compared with a reference voltage $V_{\text{ref}2}$ which sets the amount of reflectance on the reflector when its temperature has stabilized at the point of dew formation. The selection of the right $V_{\text{ref}2}$ is important, as excessive dew on the reflector results in a reflector temperature below the true dew temperature and, consequently, an underestimate of the relative humidity. The resulting signal is compared with a threshold value in the comparator circuitry which is responsible for the changes in the direction of the current in the Peltier element.

The power lost to the environment is proportional to the nonlinear element $N$ and the lag element due to the change of reflector temperature $T_{\text{mir}}$. A unity feedback loop is used for the feedback path. The aim in the design procedure of the controller transfer function (CTF) was to provide maximum gain for the derivative signal (thus decreasing the settling time of the sensor to sudden changes in relative humidity) and improve on the speed of the system.

The mark-to-space ratio of the controller is a function of the time needed to cool $T_{\text{cool}}$ and heat $T_{\text{heat}}$ the reflector and is given by $\Lambda = \left(\frac{T_{\text{cool}}}{(T_{\text{heat}} + T_{\text{cool}})}\right) \times 100\%$. The time to cool the reflector is dependent on the difference in temperature, $T_{\text{mir}} - T_{\text{amb}}$, on the thresholds of the circuit and the $P_{\text{in}}$ set by the Peltier output $T_{\text{cool}} \propto (T_{\text{mir}} - T_{\text{amb}})/(P_{\text{in}} + P_{\text{env}})$. Using similar arguments to the time to heat the reflector is given from $T_{\text{heat}} \propto (T_{\text{mir}} - T_{\text{amb}})/(P_{\text{in}} + P_{\text{env}})$ and the theoretical duty ratio can be calculated from

$$\Lambda = \frac{1}{\frac{P_{\text{in}}}{P_{\text{in}} + P_{\text{env}}} + \frac{P_{\text{env}}}{P_{\text{in}} + P_{\text{env}}}} \times 100\% = \frac{P_{\text{in}} + P_{\text{env}}}{2P_{\text{in}}} \times 100\%. \quad (13)$$

A typical mark-to-space ratio of the controller under steady state operation of the sensor is shown in figure 9.

Furthermore, the nonlinearity in the forward path of the system shown in figure 7(b), can be analysed in terms of a describing function. For a sinusoidal input, $x = X \sin(\omega t)$, to the nonlinear element, the resulting $y$ output may be expressed in terms of a Fourier series:

$$y = A_1 \sin(\omega t) + B_1 \cos(\omega t) + A_2 \sin(2\omega t) + B_2 \cos(2\omega t) + \cdots \quad (14)$$

as the nonlinear element is incapable of producing sub-harmonics. Since $G_1$ and $G_2$ have overall low-pass characteristics, it can be assumed to a good degree of approximation that all the higher harmonics of $y$ are filtered out of the process such that the input $x(t)$ to the nonlinear element $N$ is mainly contributed to the fundamental component of $y$, i.e. $x(t)$ remains sinusoidal. Under such

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**Figure 7.** (a) General block diagram of the nonfeedback loop during the operation of the dew-point sensor incorporating the STF, the CTF and the RTTF. (b) Equivalent block diagram of the nonlinear feedback loop incorporating the assumptions from small signal analysis of STF and RTTF.
conditions the harmonic content of \( y \) can be discarded for the purpose of analysis and the fundamental component of \( y \) need only be considered:

\[
y_1 = A_1 \sin(\omega t) + B_1 \cos(\omega t) = Y_1 \sin(\omega t + \phi).
\]

This treatment allows the use of a describing function \( K_N(X, \omega) = (Y_1/X)\phi_1 \) instead of the nonlinearity \( N \) with coefficients: 

\[
A_1 = \frac{1}{\pi} \int_0^{2\pi/\omega} y \sin(\omega t) \, dt \quad \text{and} \quad B_1 = \frac{1}{\pi} \int_0^{2\pi/\omega} y \cos(\omega t) \, dt,
\]

where \( y_1 = \frac{1}{\pi} \int_0^{2\pi/\omega} y \sin(\omega t) \, dt \) and \( B_1 = \frac{1}{\pi} \int_0^{2\pi/\omega} y \cos(\omega t) \, dt \), calculated from \( y_1 = \sqrt{A_1^2 + B_1^2} \) and \( \phi_1 = \tan^{-1}(B_1/A_1) \) using figure 9. The output of the Peltier switched by the MOSFETs is given by

\[
y = \begin{cases} 
H1 & \equiv P_{in} \cos(\omega t) \quad \pi/2 \leq \omega t \leq (\pi + a) \\
LO & \equiv -P_{in} \cos(\omega t) \quad (\pi + a) \leq \omega t \leq (2\pi + a) \\
H1 & \equiv P_{in} \cos(\omega t) \quad (2\pi + a) \leq \omega t \leq 5\pi/2 
\end{cases}
\]

where \( a = \sin^{-1}(H/2X) \) with \( H = 40 \text{ mV}, \omega = 15.7 \text{ rad s}^{-1} \) and \( X = 29 \text{ mV} \) so that

\[
A_1 = \frac{1}{\pi} \int_{\pi/2}^{\pi a} P_{in} \sin(\omega t) \, dt - \frac{1}{\pi} \int_{\pi a}^{2\pi a} P_{in} \sin(\omega t) \, dt
\]

It follows that \( A_1 = \frac{4P_{in}}{\pi} \sqrt{1 - \left(\frac{H}{2X}\right)^2} \) and \( B_1 = -\frac{P_{in} H}{\pi X} \), and therefore the describing function may be calculated from

\[
K_N(X) = \left\{ \sqrt{(A_1/X)^2 + (B_1/X)^2} \right\}.
\]

By replacing the nonlinearity of the system by its describing function it is possible to write a characteristic equation of the overall feedback loop and according to the Nyquist criterion the system will exhibit sustained oscillations or limit cycle when

\[
G_1(j\omega)G_2(j\omega)K_N(X, \omega) = -1
\]

and its least detectable signal will be \( X/2 \).

### 6. System performance

Complete cycles during the operation of the sensor (for the uncut, single-cut and double-cut configurations) using proportional control only are shown in figure 10. The lower trace represents the change in temperature of the PMMA film on the Peltier, whereas the upper trace shows the change in reflectance due to dew formation. For the uncut and single-cut configurations, under closed-loop operation, the surface of the reflective film is controlled to 50 mV (lower trace) which corresponds to 0.1 °C. The merits of the double-cut configuration become apparent in figure 10(c) where the scale is reduced to 20 mV. The smaller amplitude oscillations of the reflectance signals as well as the shortest period in these oscillations (5, 2 and 1 s for the traces shown in figures 10(a)−(c)) are further evidence that a tighter control loop can be achieved with the double-cut configuration.

Table 1 shows the corresponding theoretical rms variation in reflectance (equivalent to the self-noise of the optical sensor) and the optimal stand-off distances for different fibre-optic configurations. The dominant noise source in the system is the shot noise of the photodiode. This is given by \( i_n = (2eB_i)^{1/2} \), where \( e \) is the electronic charge, \( i \) is the diode current, \( B \) is the bandwidth (5.3 Hz) of the filter after the PSD and \( i_n \) is the rms noise current. In the present noise analysis, the thermal noise is also taken into consideration, using \( i_t = (4KT/R_t)^{1/2} \), where \( K \) is Boltzmann’s constant, \( T \) is the absolute temperature, and \( R_t \) (100 K) is the feedback resistor in the current-to-voltage converter. After the equivalent noise voltage of the photodiode was calculated from \( i_n \) and \( R_t \), this was converted to absolute changes in reflectance (%) providing an equivalent rms variation in reflectance due to the shot noise. The frequency of oscillation and the temperature variation on the surface of the reflector when the Peltier is operated in feedback mode are also shown. A 20 mV hysteresis in the comparator corresponds to a change in reflectance signal of 8.4% for the uncut configuration. This can be compared.
Figure 10. Complete cycles during the operation of the sensor with (a) the uncut, (b) single-cut and (c) double-cut fibre optic configurations using proportional control only. The upper trace shows the change in reflectance and the lower trace shows the change in temperature.

with reflectance signal changes of only 1.9% and 1.0% for the single-cut and double-cut configurations, respectively.

The sensitivity of the system’s reflectance setting to the reference voltage \( V_{\text{ref2}} \) when the system is operated with proportional control only is shown in figure 11. The accurate setting of this reference voltage is crucial for reliable measurement of the reflector temperature at the onset of dew formation. The sensitivity of the relative humidity to the reference voltage setting is shown in figure 12. These results show that accurate estimates of relative humidity can only be achieved within a narrow range of reference voltage (from 0.40 to 0.42 V). Once calibrated, the sensor has an excellent response time to step changes in relative humidity and ambient temperature.

Finally, it is worth noting that, if there were variations in the optical power distribution among the modes of the plastic fibre due to different light injection conditions or different optical coupling among modes during the operation of the sensor, such variations would propagate to the proportional and derivative signals used in the nonlinear control loop. Large variations could affect the original calibration of the system.

7. Discussion

Very precise control of the temperature of the reflector surface can be achieved using the signal from the highly responsive double-cut fibres. Operating around the point of inflexion of the slope of the reflectance function (onset of dew) reduces the associated problems of system sensitivity to reference reflectance setting and improves the response time of the sensor. Although many dew- or frost-point hygrometers have been described in the literature since the 1960s [11], such precise temperature control of the reflector surface has only recently been possible using a combination of capacitive

Figure 11. Sensitivity of reference reflectance setting to reference voltage \( V_{\text{ref2}} \) when only proportional control is used.

Figure 12. Sensitivity of sensor calibration to reference voltage \( V_{\text{ref2}} \) when only proportional control is used.
sensors with feedback.

A major limitation of the plastic optical fibres used is their restricted operation to maximum temperatures of 85°C. When a sample of plastic fibre is left exposed to high temperature, a transmission loss occurs from the oxidized degradation of the core polymer. Carbonyl groups are formed, and cross-linking and double-bonding of the polymer chains occur due to molecular dissociation or elimination reactions. These, in turn, induce an increase in the electron transition absorption at 660 nm and an adaptive shift towards a longer-wavelength band. It is possible to use heat-resistant plastic optical fibres with a thermoplastic resin for the core, and silicone elastomer for the cladding (Furukawa Electric Co., Japan). These fibres have a wavelength window ranging from 730 to 820 nm, and are hot-humidity resistant, showing an increase in transmission loss of only 0.2 dB m⁻¹ after 500 h of exposure at 80°C and 95% RH environment [12].

Furthermore, new polymer optical fibres fabricated by Fujitsu Co. (Japan) using ARTON™ (Japan Synthetic Rubber Co. Ltd) with high thermal stability up to 115°C, good transparency at the visible wavelength, high flexibility and high tensile strength properties, may be implemented in the new humidity sensor. The minimum optical transmission loss spectrum is 0.8 dB m⁻¹ at 680 nm and 1.2 dB m⁻¹ at 780 nm [13]. The thermal expansion of ARTON™ is much lower than that of conventional or low water absorption PMMA and can be considered negligible at high humidity.

The dew-point sensor is suitable for meteorological observations, measurements of moisture content in crops and food products (as long as the absorption isotherm is known), or water activity in agricultural products. One particular advantage is that it can function at high humidities, where other sensors are often less reliable. The relatively small size of the sensor facilitates its use in plant physiology research.

8. Conclusions

A new feedback dew-point sensor that operates around the point of dew formation has been presented. The optimized cutting of the fibres in the optical configuration permits better light coupling and reduces the stand-off distance between the reflector and the detecting fibre, giving a better signal of the onset of dew formation on the reflector. The reduction in the reflector’s optical contamination is due to the combined use of a hydrophobic PMMA thin-film reflector, the use of a feedback scheme around the point of dew formation and the improved detectivity of the onset of dew.

The use of the differential signal in conjunction with the reflectance signal decreases the system’s sensitivity to absolute reflectance setting and decreases the response time of the sensor to step changes in environmental parameters. The amplitude modulation intensity referencing scheme used provides the necessary stability required for the setting of the reference reflectance signal. Results for the sensitivity of the reflector temperature to the reference voltage setting have shown that care must be taken in the calibration of feedback configurations. Although the current system is vulnerable to fluctuations of the power distribution among modes propagating in the fibre, such effects could be minimized with the use of a mode scrambler.

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