REVISTA MEXICANA DE FÍSICA S **52** (2) 64–67 FEBRERO 2006

Refractometric fiber-optical detectors of liquids: effect of residual liquid film

K.E. Romo-Medrano
Departamento de Ingeniería Eléctrica y Electrónica,
Instituto Tecnológico y de Estudios Superiores de Monterrey, Campus Ciudad de México,
Tel.: +52 (55) 5483 2204,
e-mail: kerm@itesm.mx

K.S. Khotiaintsev
Facultad de las Ciencias de la Computación, Benemérita Universidad Autónoma de Puebla,
C.U., Puebla, Pue.
Tel: +52(222)225 5500,
e-mail: konstakh@hotmail.com

V. García-Garduño and S.N. Khotiaintsev
Facultad de Ingeniería, Universidad Nacional Autónoma de México,
C.U., México, D. F.,
Tel.: +52 (55) 5622 3055
e-mail: sergeikh@hotmail.com, victorg@verona.fi-p.unam.mx

Recibido el 27 de octubre de 2004; aceptado el 19 de mayo de 2005

We analyze the response of the optical refractometric detection element of a hemispherical shape in the presence of a contamination in the form of a film of liquid on its surface. We show that the liquid film distorts the detector's response to the refractive index of the surrounding medium. This distortion is more pronounced in the case of small-size detection elements, such as those employed in the fiber-optical refractometric sensors.

Keywords: Refractive index; refractometry; optical fiber sensors.

En el presente trabajo, analizamos la respuesta de un transductor óptico refractométrico de una forma semiesférica, cuando su superficie esta contaminada por una película de líquido. Demostramos que la película de líquido distorsiona la respuesta del transductor al índice de refracción del medio externo. Esta distorsión es más pronunciada en el caso de los transductores miniatura, como los utilizados en los sensores refractometritos de fibra óptica.

Descriptores: Índice de refracción; refractometría; sensores de fibra óptica.

PACS: 42.81 Pa; 42.81Wg

1. Introduction

In recent years, fiber-optical refractometric sensors have proven their utility in laboratory experiments and in industrial conditions [1-3] because of their small size, immunity to electromagnetic interference, ability to work in hazardous media, etc. The fiber-optical refractometric sensors are used:

1) for the refractive index measurement of fluids, and
2) for liquid level measurement [4].

However, any contamination of the optical detection element's surface can distort the sensor's response to the refractive index of the surrounding medium. Among all possible types of contamination, the presence of a residual film of liquid on the sensor's surface is the most common case. There is a large variety of liquid substances that can contaminate the optical detection element's surface during the exploitation of the sensor. Also, the quantity of liquid on the element's surface may be different and it can form different geometrical shapes. Because of this, the analysis of the effect of the contaminating liquid film on the sensor's response presents a complex non-trivial problem.

In this work, we analyze the effect of the residual liquid film, of different shapes and thicknesses covering the optical detection element's surface, on the performance of the refractometric sensor. The present study is restricted to the case of the hemispherical fiber-optical refractometric detection elements described in our previous works [4,5]. The refractometric sensors of this type have already found a variety of important applications in scientific research and industry.

2. Sensor description

We considered a refractometric transducer composed of a hemispherical solid transparent dielectric detection element and a pair of step-index multimode optical fibers (Fig. 1) that connect the detection element with the remote light source and the photometer (not shown in Fig. 1) [4,5]. The two optical fibers are coupled due to the internal reflection of light at the element's hemispherical surface when the element is in the air. The optical transmission of the element depends on the refractive index of the surrounding medium n and thus serves to access this quantity. In order to exclude the intrinsic optical loss in the detection element, the transducer's relative transmission $T^*(n)$ is employed:

$$T^*(n) = \frac{T(n)}{T_{air}} = \frac{I_2(n)}{I_{2air}}, \quad (1)$$

T_{air}, I_{2air} are the transducer's transmission and the output light intensity respectively when the surrounding medium is the air [5]. For the case of a clean transducer surface (no contaminating liquid film on it), the behavior of T_{air} and $T^*(n)$ under different combinations of the transducer parameters is studied in detail in Ref. 5.

The liquid film that remains on the detection element surface after it has been in contact with a liquid has the shape of a drop, which may have a different volume and form. The refractive index of the liquid n_f may be rather close to that of the optical detection element n_e. In this case, the internal reflection may take place mainly on the liquid film surface and not on the glass surface. This leads to the distortion of the transducer's transmission in the air T_{air}, which is important for the transducer calibration and derivation of $T^*(n)$ in accordance with (1).

The particular parameters of the liquid film depend on the liquid viscosity, wetting, and detection element orientation in space. In this work, we have considered three principal cases of the detection element position as shown in Fig. 2. We assumed that the spatial form of the liquid film was an ellipsoid in the cases (d) and (f), and a symmetrical paraboloid in case (b). The parameter that we changed was the liquid drop's dimensionless height H in the case of the vertical "down" position of the detection element (Fig. 2b), the liquid drop's dimensionless radius R in the case of the vertical "up" position of the detection element (Fig. 2d), and the liquid drop's dimensionless radius R and height H in the case of the horizontal sideways position of the detection element (Fig. 2f).

3. Results

We calculated T_{air} and $T^*(n)$ by means of numerical ray-tracing, employing a specially developed computer program. The data were obtained under the following parameters: a symmetric position of the two identical step-index multimode optical fibers at a dimensionless distance Λ=0.707R with respect to the transducer axis, the detection element radius R = 1; the fiber core radius r = 0.05; the optical fiber numerical aperture in the air *NA* = 0.2; the refractive index of the fiber core is equal to that of the detection element n_e = 1.55. We employed these parameters because they were used in Ref. 5. In the present work, we assumed the refractive index of a liquid n_f equal to that of the optical detection element n_e: $n_f = n_e$ = 1.55.

The detection element oriented vertical down.

The paraboloidal detection elements of Figs. 3b and 3c are represented by the equations $z = 0.714x^2 + 0.714y^2 - 1.5$ and $z = 0.714x^2 + 0.714y^2 - 2$ respectively. The results of the numerical ray-tracing are shown in Fig. 3, a-c. One can see in Fig. 3 that, in spite of the change in form and size of the element's surface due to the formation of the drop of liquid on it (from a to b and then c), there exists a sufficiently good coupling between the transmitting and receiving optical

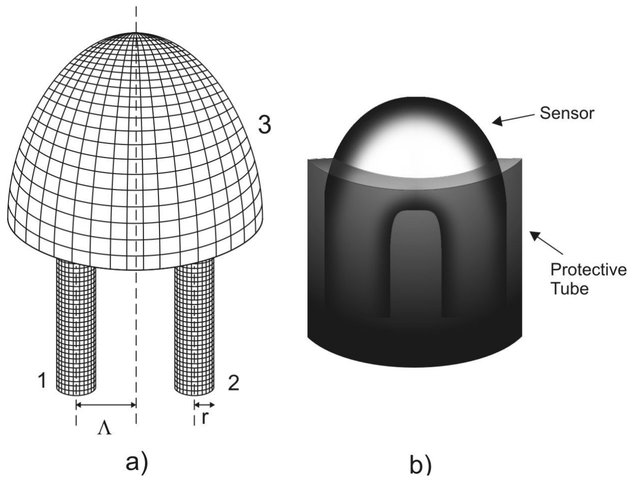

FIGURE 1. Generic refractometric transducer with hemispherical optical detection element (a); the refractometric transducer in the protective tubular housing (b).

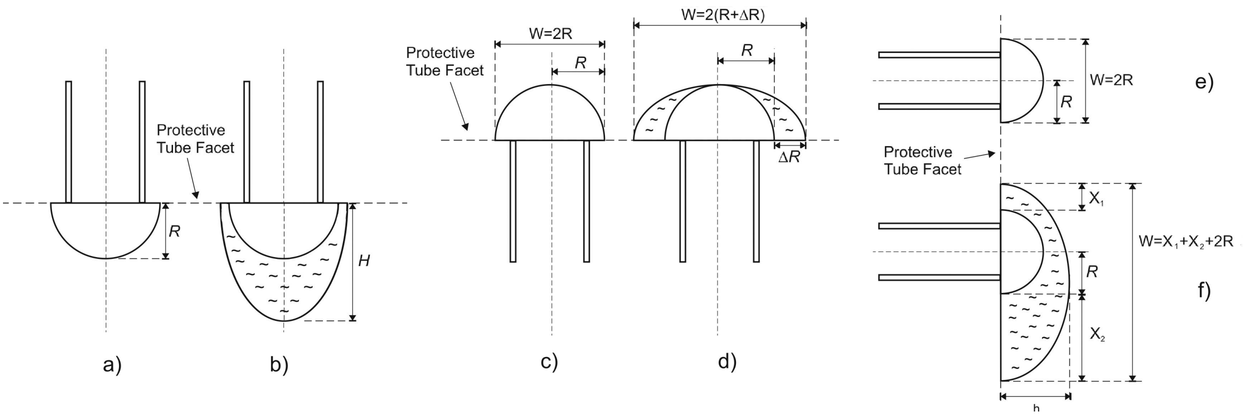

FIGURE 2. Different positions of the refractometric transducer and the resulting shape of the residual liquid film on its surface: vertical down position (a,b); vertical up position (c,d); horizontal sideways position (e,f).

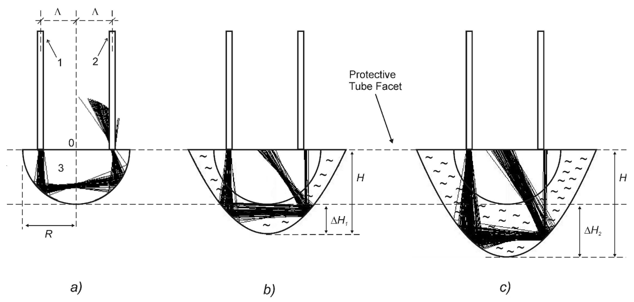

FIGURE 3. Light propagation in the refractometric transducer in the case of vertical down position, in the air: clean transducer surface (a); relatively small drop of liquid stuck to the surface (b); large drop of liquid stuck to the surface (c).

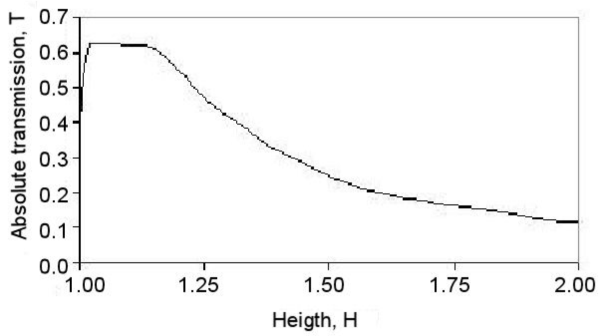

FIGURE 4. Transducer transmission in the air T_{air} versus detection element's dimensionless effective height H.

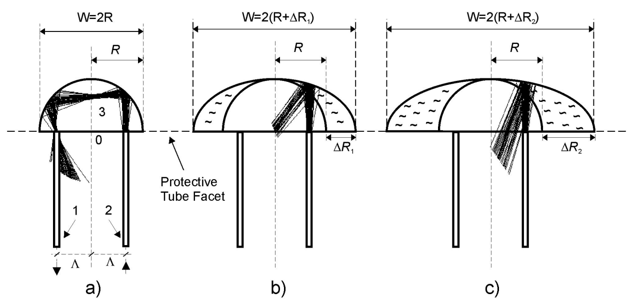

FIGURE 5. Light propagation in the refractometric transducer in the case of the vertical up position, in the air: clean transducer surface (a); small amount of liquid stuck to the surface (b); relatively large amount of liquid stuck to the transducer surface (c)

fibers. This is due to the fact that with the increase in the liquid drop volume, it extends mainly downwards (the height of the paraboloid H increases). The element's resulting surface curvature and local radius do not experience a drastic change in the regions where the optical beam is reflected internally. In addition, the incidence angle increases at some reflection points. Altogether, this contributes to an increase in the optical beam diameter, which in turn makes the coupling between the two optical fibers less critical to the deviations of the detection element surface from its ideal hemispherical shape. The quantitative data on the effect of the height H on T_{air} are plotted in Fig. 4. One can see that for the interval 1< H <1.3. the absolute transmission T increases, due to a better coupling of the optical fibers. For $H < 1.3$, T decreases monotonically with the increase in H reaching $T \approx 0.12$ at $H = 2$.

The detection element oriented vertical up.

The equations that describe the ellipsoids of Figs. 5 b, c are:

$$\frac{1}{2.25}x^2 + 1y^2 + 1z^2 = 1 \tag{2}$$

and

$$\frac{1}{4}x^2 + 1y^2 + 1z^2 = 1 \tag{3}$$

respectively. Unlike from the previous case, as shown in Fig. 5, the increase in the liquid drop size and volume results primarily in the increase in the drop's width $W = 2(R + \Delta R)$ and not its height H. The detection element surface becomes flatter, the incidence angle is reduced (Figs. 5b,c) with respect to the clean surface case (Fig. 5a), the optical beam becomes less divergent than in the case of the clean surface, and the number of serial internal reflections reduces to just one. These changes contribute to an abrupt decrease and then complete vanishing of the optical coupling of the transmitting and receiving fibers.

The detection element oriented horizontally sideways

The equations that describe the ellipsoid of Fig. 6b is:

$$\frac{1}{4}x^2 + 1y^2 + \frac{1}{2.25}z^2 = 1. \tag{4}$$

One can see in Fig. 6, that the effective surface of the detection element becomes flatter than the surface of the clean glass element. In addition, the whole effective surface is displaced downwards with respect to the element's axis. The combination of these two factors leads to an even more rapid decrease and the vanishing of the optical coupling in the transducer than the previous case of the vertical upwards orientation of the detection element. Quantitative analyses show

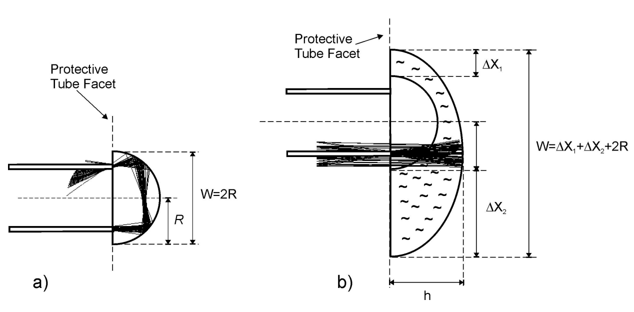

FIGURE 6. Light propagation in the refractometric transducer in the case of the horizontal sideways position, in the air: clean transducer surface (a); a drop of liquid stuck to the transducer surface (b).

that under the liquid drop's dimensionless radius R as small as R=1.06 and dimensionless height H=1.5, the optical coupling vanishes completely in the transducer.

The approach developed in this work permits one to determine the effect of the residual liquid film on the performance of various refractometric transducers and different geometrical parameters of optical detection elements, liquid films and material constants.

4. Conclusions

A residual liquid film on the surface of the hemispherical optical detection element of the fiber-optical refractometric transducer can significantly alter the transducer response (its optical transmission) in the air, which is used for transducer calibration. The amount of the effect depends on the thickness of the liquid film, its shape, and on the spatial orientation of the transducer. The vertical downward orientation of the transducer secures the minimum effect of the residual liquid film. The horizontal sideways position is the worst one, because the distortions of the optical detection element surface are the most severe in this case. The effect of the residual liquid is more significant in the case of small-size detection elements, such as those employed in the fiber-optical refractometric sensors.

1. A. Cartelier, *Rev. Sci. Instrum*. **63** (1992) 5442.
2. V. De León and S. Khotiaintsev, *Instrumentation and Development* **4** (1999) 31.
3. V. Svirid, V. De León, and S. Khotiaintsev, *Institute of Electronics, Informatics and Communications Engineers (IEICE) Transactions on Electronics* (Japan) **E83-C** (2000) 303.
4. K.E. Romo-Medrano *et al.*, *Multiplexed Optical Fiber System for Monitoring the Void Fraction Distribution in Fuel/Gas Centrifuge Separator of a Spacecraft*, Technical Digest, 16^{th} International Conference on Optical Fiber Sensors Japan, The Institute of Electronics, Information and Communication Engineers (IEICE) (2003) 424.
5. V. Svirid, S. Khotiaintsev, and P.L. Swart, *Optical Engineering* **42** (2003) 1383.