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WET STEAM TURBINES : STEAM TEMPERATURE AND SUBCOOLING MEASUREMENT BY FIBER OPTIC SENSOR

I - OBJECTIVE

In wet steam study, the subcooling achieved by the flow - i.e the temperature departure for equilibrium $\Delta T = T_s - T$ - is the main factor controlling the primary fog formation.

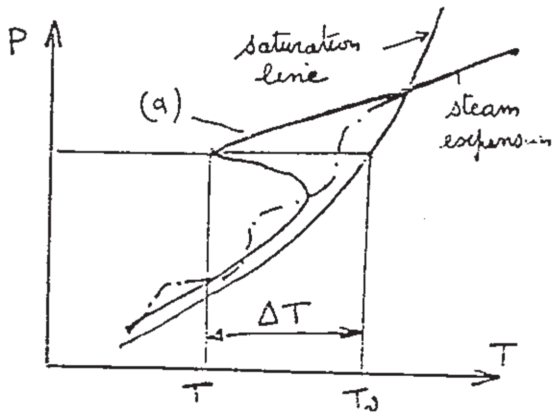

Fig.1 - Subcooling

Figure 1 (curve a) shows a typical decrease in temperature (obtained only by calculation) when steam expands in a supersonic nozzle. In turbine this evolution (curve b) is more sophisticated because expansion takes place in several stages and several secondary phenomena such as heterogeneous condensation on foreign nuclei, fluctuations, 3.D flow effects etc.. can affect subcooling. So direct measurement of static temperature (the saturation temperature $T_s(p)$ is easily calculated through the knowledge of the pressure measured, for example by a five holes probe) will give vital informations on the factors controlling the wetness formation.

III - PRINCIPLE OF THE OPTICAL SENSOR

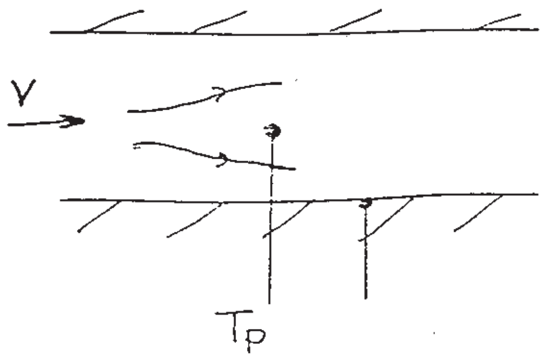

Fig.2 - Classical Probe

Classical temperature measurements consist of either introducing a probe in the flow or measuring wall temperature. By doing so, it is well known that the probe detects an increase of temperature due to flow friction

$$T_p = T + \zeta \frac{V^2}{2\,C_p} \quad \# \quad T_{total}$$

with ζ (recovery factor) # 1

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In supersonic flow $\Delta T_p = T_p - T$, can achieve values up to 40° K greater than the subcooling we try to measure.

Thus a static temperature probe must have two main characteristics :

- be non-intrusive
- be compactness to be introduced in turbine (maxi diameter 25 mm)

The proposed system is based on interferometric measuring of optical refractive index variations of a steam volume induced by temperature variations.

The basic principle is shown in fig. 3.

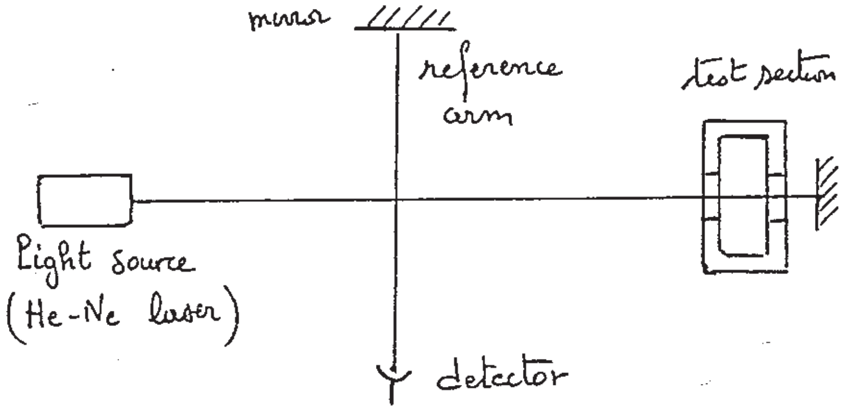

fig. 3 . Single mode fiber Michelson interferometer

The test section is placed in the measuring arm of an interferometer; a photodiode detects a signal having the form : $I = Cst + I_0 \cos(\Delta\phi \div \Delta\phi_T)$ (1)

$\Delta\phi$ is initial phase and $\Delta\phi_T$ is the phase variation induced by thermal effects

$$\Delta\phi_T = \frac{2\pi}{\lambda} 2 \, \Delta \, (nl) \qquad (2)$$

where n is the refractive index of steam, l the width of the channel, and λ the wavelength of the laser.

If is maintained constant, $\Delta\phi_T = \frac{4\pi l}{\lambda} \Delta n$

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Using Gladstone-Dale relation between n and the specific mass $[(n - 1) = k\rho]$ and assuming steam obeys the perfect gaz law $[\frac{P}{\rho} = RT]$ one can deduce the variation of the static temperature. For example if the pressure is maintained constant

$$\Delta n \doteq k\rho \frac{\Delta T}{T} \qquad (3)$$

with $k \# 280\ 10^{-6}$ for low pressure steam.

The thermal resolution sought is about 1 K for a measuring range of 50° K. From eq. 3, the variation of 1 K corresponds to a phase variation of only 20° (or approximately to a length variation of $\frac{\lambda}{10} = 0{,}0628\mu m$)

III - REALISATION

To resolve both modelisation problems, great sensitivity (1 K) and dynamic (at least 50 K) we have proposed a new interferometric structure in which the two beams (reference and signal) propagate in the same fiber. The second fiber of the coupler is not used. the reference beam is formed by the Fresnel reflexion at the end of the polished fiber (≃4%) (fig.4). The measurement beam (96 %) goes through the flow pipe, is reflected by a mirror and goes back into the fiber, so doubling the effect. The end of the fiber and the mirror are supported by a sophisticated mechanical structure called "sensor head".

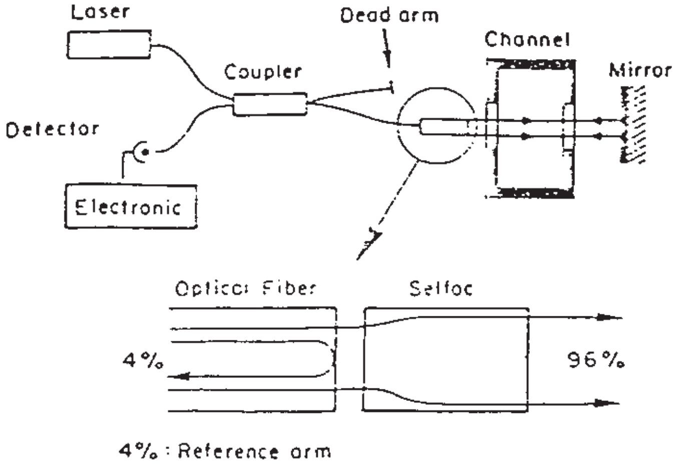

Figure 4. Michelson interferometer single physical arm.

Detection : An active phase tracking heterodyne detection has been chosen. A lock-in amplifier extracts the harmonic at twice the phase modulation (the mirror is driven by a piezoelectric plate modulator). This signal is amplified and fedback to the piezoelectric plate in order to compensate the optical path variation thermaly induced in the sensor head.

The diagram of the detection is as follow :

The optical signal collected by the photo detector may be represented by :

(4) $I(t) = \text{Const.} + I.\cos(\Delta\phi + \Delta\phi_T + a\cos\omega t)$ where a, ω are the amplitude and the frequency of the phase modulation; $\Delta\phi$ and $\Delta\phi_T$ the initial phase difference and the variation of phase due to the temperature variations.

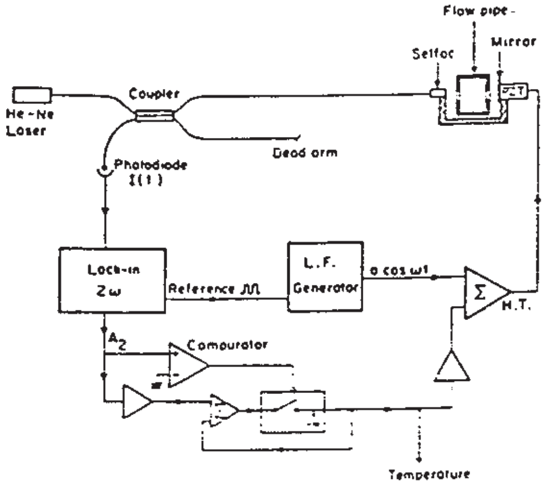

Figure 5. Active phase tracking heterodyne detection.

If we develop relation (4) in terms of Fourier serie, the second harmonic (in $2\,\omega$) is :

$$I_{2\omega} = -\,2\ I_0\ J_2\ (a)\ \cos\ (\Delta\phi + \Delta\phi_T)\sin\ 2\omega t$$

where J_2 (a) is a Bessel's function; this term has been chosen and extracted because it is proportionnal to the cosinus of the phase : vanishing of this term i.e $\Delta\phi + \Delta\phi_T = \pi/2 + 2n\pi$ corresponds to maximum Michelson interferometer sensitivity (when the reference and signal are in quadrature).

The principle of the phase nulling detection is to add algebricaly a voltage ΔV on the piezoelectric to get $I_{2\omega} = 0$. This voltage (feedback signal) is proportionnal to the optical path variation in the sensor head. This coefficient is determined by placing the sensor head in a vaccum drying oven. Foreign lenght variations due to thermal effects on the sensor head components (selfoc lens, metal...) can be auto-compensated by the opposite thermal variation of an adjusting plate (al) placed between the mirror and the piezoelectric modulator.

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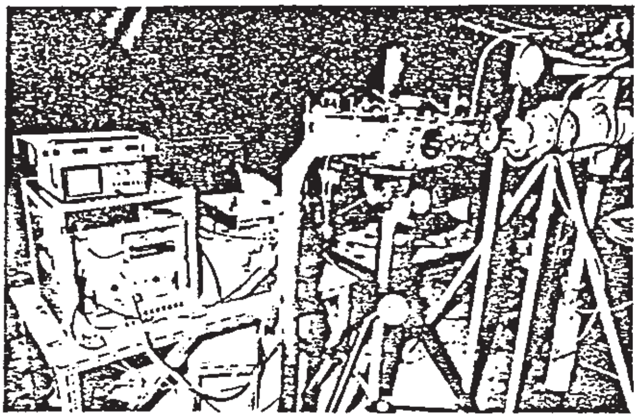
IV - EXPERIMENTATIONS

Different experiments have been made in order to demonstrate the feasability of this sensor (photography 1) :

- i) in dry air flow at low velocity,
- ii) in supersonic dry air flow,
- iii) in steam expansion.



Photography 1. The optical fiber themometer installed around the flow pipe.

Photography 1. Optical fiber thermodynamic installed around the flow pipe

i) Temperature measurement in dry air flow at low velocity (20 m/s)

Here velocity influence is negligeable : dynamic temperature $(V^2/2c_p)$ is less than 0.1 K. Thus it is possible to compare optical and usual measurements (thermocouple). Figure 5 shows results obtained in this experiment, the resolution is better than 0,5 K.

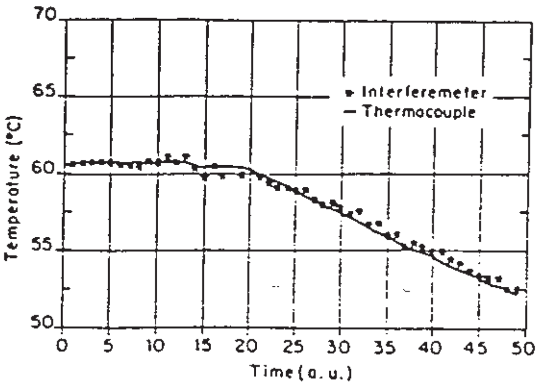


Figure 5. Temperature measurement in dry air.

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ii) Temperature measurement in supersonic dry air flow

In this experiment, we set a convergent-divergent profile in the air pipe (figure 6), exhausting at atmospheric pressure :

P_0 varies from 1 to 2 bars and T_0 is still constant at 293 K

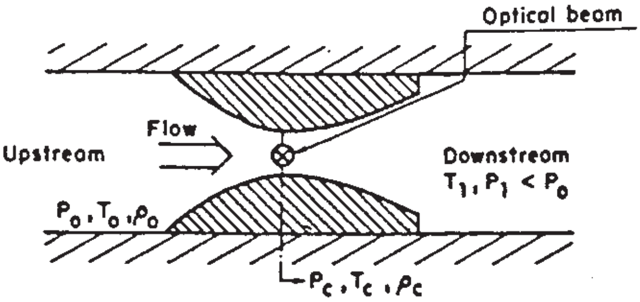

Figure 6. Throat temperature measurement.

Location of measurement has been chosen at the throat of the nozzle. The temperature, pressure and specific mass can be calculated theoretically by assuming air is a perfect gas. In particular when the sonic flow rate is achieved, P_c and T_c are proportionnal to P_0 and T_0 respectively.

$$P_c = P_0 \quad (2/(\gamma + 1))^{(\gamma/(\gamma-1))} \qquad\qquad P_c = 0.528 \; P_0$$

$$T_c = T_0 \; [2/(\gamma + 1)] \qquad\qquad T_c = 0.833 \; T_0$$

(in our experiment T_0 = cte = 293 K)

The sonic conditions are obtained when P_0 is up to critical value P_0^*, depending on the ratio between throat and exit nozzle area A_c/A_g.

Using the relation (P/ρ^γ) = cte = $(P_0/\rho_0)^\gamma$ for isentropic flow and $P/\rho = RT$ for perfect gas law; T_c and P_c can be deduced from the refractive index measurement and then compared to the theoritical values (figure 8).

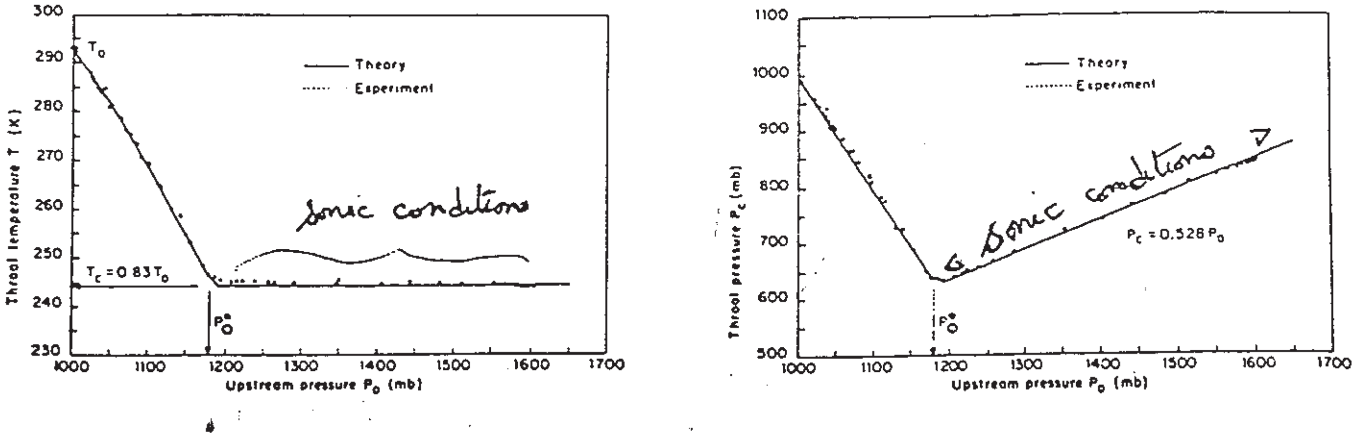

Figure 8. Optical throat temperature and pressure measurement vs. upstream pressure.

A very closed agreement is achieved between experiment and theoritical curves.

Thus, we deduce temperature difference :

$$T_0 - T_c = 49 \text{ K}$$

with a resolution of 0.5 K

To conclude, the sensor gives very good measurement in supersonic air flow, in spite of a noisy environment (vibrations).

iii) Temperature measurement in steam

In this experiment, the set-up is exactly the same as the previous one, but now steam is flowing in the pipe instead of dry air.

Unfortunately, the piezoelectric modulator driving the mirror was burnt by the steam (100° C) momentarily interupting our investigation !

It is necessary to choose components for the turbine probe ($T \neq 100°$ C) with care as shown by this failure.

Compact probe for measurements in turbines

Effective operation of this temperature sensor in the supersonic air pipe in the Gennevilliers power plant has been shown. Consequently we have designed a prototype of a probe for experiments in steam turbines (figures 9 and 10).

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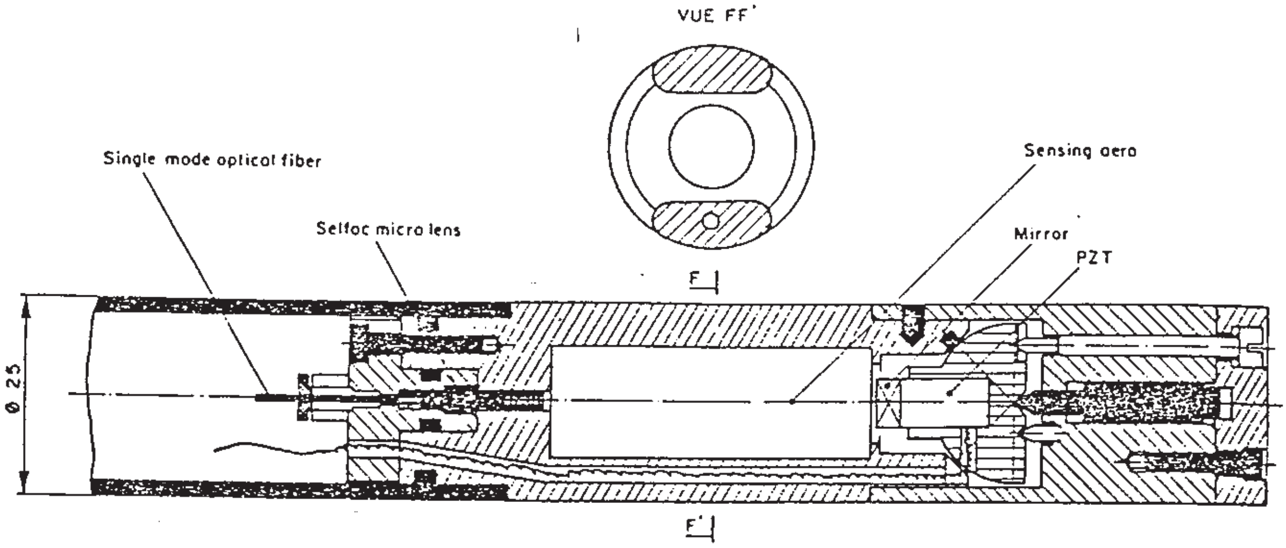

Figure 9. Sensing head probe for temperature measurement in turbine.

In order to cancel the previous problem of temperature behaviour of glass windows, we have chosen two different types of glass with opposite optical path variations (Schott AF 22 and FK51)

The sensor principle is the same as the first sensor.

Auto-thermal compensating of this new sensor head will be adjusted in a vaccum drying oven.

This new protoype of temperature sensor wil be tried in turbines in the middle of 1988.

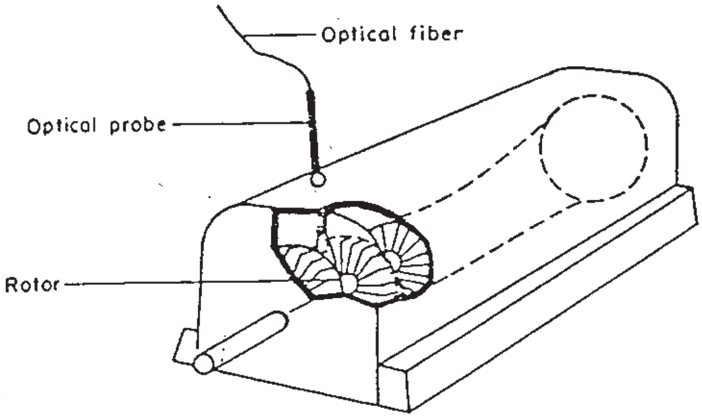

Figure 10. Temperature measurements in steam turbine with optical probe.

CONCLUSIONS

A special type of optical fiber sensor has been studied to detect temperature in steam flows. Very good stability is obtained with a Michelson interferometer single physical arm combined with an active phase tracking heterodyne detection.

Feasibility has been demonstrate after numerous tests, including drying-room experiments, long-time records and flow pipe tests.

The sensor developed supply results which agree quite well with thermodynamic theory.

A resolution of 0.5 K with an integration path of 2 centimeters and a time response of the system (optic and electronic) better thant 0.5 second has been proved.

A very compact probe is now ready to be tested in turbines.

Moreover, this new technique seems to be very useful in acoustics for density fluctuations in flows.

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