# MEASUREMENT OF TURBULENT PRESSURE AND
# VELOCITY FLUCTUATIONS IN A VAPOR FLOW
# BY THE CONDENSATION METHOD

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The inertial characteristics of the thermal processes underlying a new method of measuring turbulent pressure and velocity fluctuations are analyzed.

If a surface coated with a condensate film is placed normal to a turbulent flow of pure dry vapor, the temperature of the surface film will very rapidly follow the fluctuations of the total vapor pressure in time. It is obvious that the rate of relaxation of the pressure—temperature equilibrium on the film surface due to the rapid molecular processes of evaporation and condensation will be significantly greater than the greatest possible rates of pressure change due to turbulence. It is also obvious that if the variation of temperature of a sufficiently small area of the film surface could be measured, the interpretation of the data obtained in this way from the known saturation line for the working fluid would give accurate information about the corresponding turbulent pressure and velocity fluctuations. Since the thin condensate film on the sensitive surface can probably be most conveniently formed by condensation, and this process takes part simultaneously in the relaxation phenomena, this measurement technique can be called the condensation method.

These physical premises provide the basis for a new method of measuring turbulent pressure and velocity fluctuations in a vapor flow. The proposed method, as reported in [1], can theoretically have a resolving power approximately one order greater than that of a hot-wire anemometer (which measures turbulent eddies of a scale of 500 $\mu$ or more [2, 3]). Another advantage of the method is the obvious reliability of interpretation of pressure fluctuations from the temperature fluctuations on the basis of the saturation line. The interpretation of thermoanemometer readings, which is usually based on calibration curves obtained for the case of steady heat transfer of the wire, cannot be regarded as strictly accurate [3]. The fluctuations of film surface temperature, on the other hand, for the same turbulent fluctuations have much smaller amplitudes than the temperature fluctuations of the hot wire of the anemometer; hence, the sensitivity of the sensors and amplifying equipment must satisfy rigorous requirements. The subject of the present investigation was an analysis of the characteristics obtained by this method when the temperature fluctuations of the condensate film surface were measured by a sensor converting these fluctuations to electrical quantities.

The analysis is based on the application of the method illustrated in Fig. 1. The end face of a metal cylinder 1 of very small diameter is covered with a thin film of another metal. Together they form a thermocouple, and their interface acts as a converter of temperature to emf. Heat is led away from the cylinder along the x axis in such a way that at cross section $x = l$ the temperature is constant in time and is a little less than the vapor saturation temperature (the vapor flow is normal to the end face of the cylinder). Cooling at a low rate produces a thin film 2 of condensate on the end face. The side surface of the cylinder is covered with a layer of heat insulation; hence, in view of the high thermal conductivity of the cylinder itself and the smallness of the length $l$, heat transfer in a lateral direction can be neglected (the insulating layer is not shown in Fig. 1). Modern technology, of course, can provide the second electrode of the thermocouple and the corresponding switching system in the form of very fine films (of the order of $10^{-1}$-$10^{-2}$ $\mu$ thick) deposited without any contact thermal resistance; hence, the latter has practically
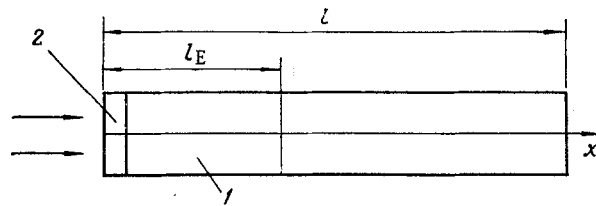
Fig. 1. Diagram illustrating application of process: 1) metal cylinder; 2) condensate film.

no effect in the case of the unsteady thermal-conduction processes taking place in the system formed by the condensate film and the cooled cylinder (this layer and the switching system are not shown in Fig. 1). In view of this, the condensate—metal interface can be regarded as the converting layer. We can also assume that heat transfer through the film is due entirely to molecular thermal conduction owing to the very small thickness and area of the film. The subject of analysis is the process of penetration of periodic temperature fluctuations, with a prescribed frequency and amplitude at x = 0, along the x axis. The aim of the analysis is to determine the distortion (reduction) of amplitude and the shift of phase of the temperature fluctuations by the time they reach the converting layer.

To simplify the calculations, we replace the cylinder shown in Fig. 1, which has an adiabatic lateral surface consisting of condensate and metal, by a uniform cylinder with the same thermal diffusivity as the condensate, which is equivalent from the viewpoint of propagation of periodic thermal waves. It follows from the known solutions of similar problems of unsteady thermal conduction [4] that in the definition of the length of the equivalent uniform cylinder the metal part must be replaced by a length of condensate given by

$$\frac{1}{a_M} \sqrt{\frac{\omega}{2}} \, l_m = \frac{1}{a_C} \sqrt{\frac{\omega}{2}} \, l_{CE}. \tag{1}$$

With the adopted premises the analysis of the considered process reduces to the solution of the following boundary-value problem:

$$\frac{\partial T}{\partial \tau} = a_C^2 \frac{\partial^2 T}{\partial x^2} \,,$$

$$T(x, 0) = \varphi(x) \quad (0 < x < l_E), \tag{2}$$

$$T(0, \tau) = A \cos \omega \tau; \quad T(l_E, \tau) = T_0 \quad (0 < \tau < \infty).$$

We seek the solution in the form

$$T(x, \tau) = \frac{x}{l_E} \, T_0 + R(x, \tau) + V(x, \tau), \tag{3}$$

where R(x, τ) is the solution of the boundary-value problem

$$\frac{\partial R}{\partial \tau} = a_C^2 \frac{\partial^2 R}{\partial x^2} \quad (0 < x < l_E),$$

$$R(0, \tau) = R(l_E, \tau) = 0 \quad (0 < \tau < \infty), \tag{4}$$

$$R(x, 0) = \varphi(x) - V(x, 0) - \frac{x}{l_E} \, T_0 = \varphi_1(x),$$

and V(x, τ) can be found as the real part of a particular solution of the boundary-value problem

$$\frac{\partial U}{\partial \tau} = a_C^2 \frac{\partial^2 U}{\partial x^2} \quad (0 < \tau < \infty), \tag{5}$$

$$U(0, \tau) = A \exp(i\omega\tau); \quad U(l_E, \tau) = 0 \quad (0 < x < l_E).$$

Here V(x, τ) = ReU(x, τ). The general solution of the given problem has the form

$$T(x, \tau) = \frac{x}{l_E} \, T_0 + \sum_{n=1}^{\infty} b_n \exp\left[-\left(\frac{n\pi a_C}{l_E}\right)^2 \tau\right] \sin \frac{n\pi}{l_E} \, x +$$

$$+ A \left[\frac{\operatorname{ch} k(2l_E - x) \cos kx - \operatorname{ch} kx \cos k(2l_E - x)}{\operatorname{ch} 2kl_E - \cos 2kl_E} \cos \omega\tau + \right.$$

$$+ \frac{\operatorname{sh} k\,(2l_{\mathrm{E}} - x)\sin kx - \operatorname{sh} kx \sin k\,(2l_{\mathrm{E}} - x)}{\operatorname{ch} 2kl_{\mathrm{E}} - \cos 2kl_{\mathrm{E}}}\ \sin \omega \tau \bigg]. \qquad (6)$$

As $\tau \to \infty$ the required solution of system (2) takes the form

$$T\,(x,\ \tau) = \frac{x}{l_{\mathrm{E}}}\ T_0 + A_x \sin \left[ \omega \tau + \operatorname{arctg} \frac{M\,(x)}{N\,(x)} \right], \qquad (7)$$

where

$$A_x = \frac{A}{\operatorname{ch} 2kl_{\mathrm{E}} - \cos 2kl_{\mathrm{E}}}\ \sqrt{M^2\,(x) + N^2\,(x)}. \qquad (8)$$

An analysis of the obtained results leads to several interesting conclusions. First, the form of solution (7) shows that the condition (1) used to fix the equivalent length is perfectly valid in the case of this specific problem. In addition, substitution of numerical data in relationships (7) and (8) shows that in the case of a water vapor flow, sufficiently accurate conversion of temperature fluctuations to emf fluctuations [with not more than 10% distortion of the fluctuation amplitude at the highest possible frequency (10 KHz)] can be obtained when the condensate film has a thickness of a few tenths of a micron. A consideration of the corresponding condensation processes shows that the production of such thin condensate films, although fairly difficult technically, does not raise any fundamental difficulties in view of the very small area of condensate surface. This factor is of fundamental importance for the proposed measurement technique. Since the condensate film is actually part of the fluctuation converter, and its thickness may vary in a certain range during measurement, the distortions introduced by such a converter cannot be compensated by any correcting components in the electronics. Hence, the proposed method will give reliable data only within the frequency range in which the transducer converts the temperature fluctuations of the condensate film surface to emf fluctuations almost instantaneously and without distortion. For a water condensate film of the order of 0.1 $\mu$ thick, for instance, the upper frequency limit exceeds 10 kHz.

## NOTATION

T, temperature; $\tau$, time; $\omega$, fluctuation frequency; $a_{\mathrm{C}}$, $a_{\mathrm{M}}$, thermal diffusivities of condensate and metal; x, distance along cylinder; $l$, length of converter with condensate film; $l_{\mathrm{E}}$, length of equivalent uniform cylinder; $l_{\mathrm{M}}$, length of metal cylinder; $l_{\mathrm{CE}}$, length of condensate column equivalent to length of metal cylinder $l_{\mathrm{M}}$; A, amplitude of temperature fluctuations on film surface.

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