HOT-WIRE AND HOT-FILM ANEMOMETRY

C. . Rasmussen and B. B. Madsen

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION
LANGLEY RESEARCH CENTER
MAY 1979

1. Report No. NASA TM-75413	2. Government Accession No.	3. Recipient's Catalog No.	
4. Title and Subtitle HOT-WIRE AND HOT-FILM ANEMOMETRY		5. Report Date May 1979	
		6. Performing Organization Code	
7. Author(s) C. G. Rasmussen and B. B. Madsen		8. Performing Organization Report No.	
		10. Work Unit No.	
9. Performing Organization Name and Address .SCITRAN Box 5456 Santa Barbara, CA 93108		11. Contract or Grant No. NASW-3198	
		13. Type of Report and Period Covered Translation	
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546		14. Sponsoring Agency Code	

15. Supplementary Notes

Translation of "Hitzdraht- und Heissfilm- Anemometrie", Archiv fur technisches Messen und Industrielle Messtechnik, February 1978, pp R17-R22 (A68-23626)

16. Abstract.

Hot-wire and hot-film anemometers, their circuit techniques; the dynamic properties of probes, the electronics of the anemometer as well as application of such devices, are the subject of this article.

17. Key Words (Selected by Author(s))		18. Distribution Statement Unclassified - Unlimited		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified		21. No. of Pages 18	22.

HOT-WIRE AND HOT-FILM ANEMOMETRY*

C. G. Rasmussen and B. B. Madsen

1. Introduction /R17*

Thanks to manifold advantages, the hot-wire and hot-film anemo-
meter has gained increasing importance investigating the micro-structure
of time and space variable velocity fields of flowing gases and fluids.
What is meant here by "micro-structure of velocity fields" is always
the instantaneous value for the velocity of particles which in terms
of volume are small compared to the total flow but large compared to
molecular dimensions.

Such studies are important for understanding and describing various
complicated macriscopic flow actions, as for example the static and
dynamic forces having an effect upon a body found in the flow, the
response time of valves and other flow controlling equipment, the flow
resistance of pipes, the research of actions in flow boundary layers,
heat exchange problems, the blending of gases and many more others.

A small, sensitive transducer is needed in addition to this with
the shortest possible response time and no disturbing effect on the flow
to be investigated.

In this paper the measuring principle and the design of the meas-
uring sensors are to be explained to begin with; then follows a short
description of the circuit techniques of anemometers, and in conclusion
some typical examples for use will be covered.

---

*Report of DISA Elektronik A/S, Herlev/Denmark
**Numbers in margins indicate pagination in original foreign text.

1

2. Hot-wire and Hot-film Tranducer

The measuring sensor of the anemometer is either a thin wire
stretched between two tips or a thin metal film coated on a glass body.
This wire or film is heated up electrically, with the dissipated
heat of the flow or the supplied electrical input being a gauge for
the velocity of the flow medium.

The strength of wire probes is sufficient to be usable in gases
up to high flow velocities (for example in atmospheric, pure air up
to low supersonic velocities) in the same way wire probes are employ-
able in non-conductive fluids at low flow velocities.

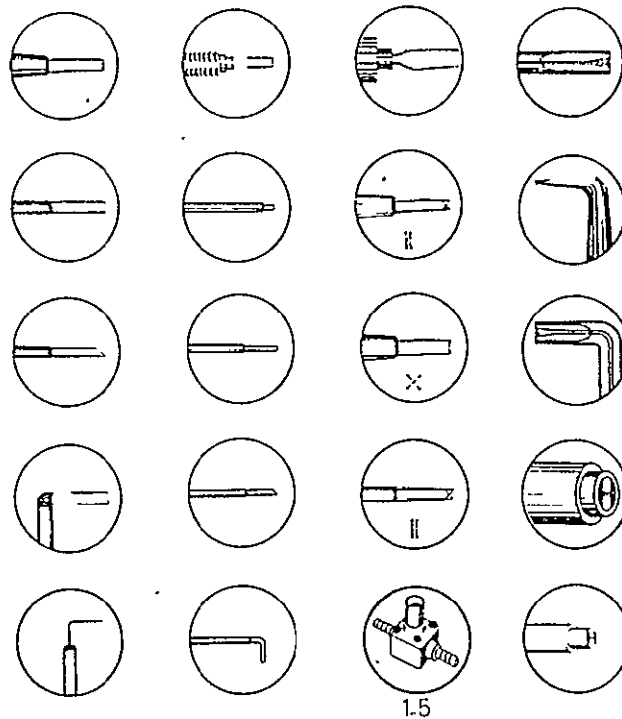Diagram 1 shows the model types of various hot-wire and hot-film
probes.

Diagram 1. Model types of various hot-wire and hot-film probes.

2.1. Static properties of probes

The laws of convective heat dissipation are the basis for the
use of heated sensor elements to measure the particle velocities in
flows. The connection between the particle velocity and the heat
dissipation is in general too complicated for a theoretical

2

consideration; it therefore has to be determined experimentally apply-
the laws of similarity.

What is more, the heat is dissipated both by natural convection
and the wire terminals or the material of the film carrier.

A theoretical solution was found by L. V. King [1] in 1914 for the <u>/R 1£</u>
heat dissipation of a uniformly heated cylinder, pre-supposing a two-
dimensional incompressible and friction-free potential flow. For
the product from Prandtl's number (= Péclét's number) larger than 0.08,
King's solution can be approximated by the following equation, using
the symbols given in the appendix:

$$Q = kl \left(1 + \sqrt{\frac{2\pi \varrho c_p d U}{k}}\right)(T - T_0) \tag{1}$$

or — dimensionless — by

$$Nu = \frac{1}{\pi} + \sqrt{\frac{2}{\pi} Re \cdot Pr.} \tag{2}$$

But the pre-conditions assumed by King are not completely correct,
and even the heat dissipation is of a more complex nature. More
recent experiments by Collis and Williams [2] have shown that the
equation

$$Nu = \left(\frac{T_m}{T_0}\right)^{0,17} (0.24 + 0.56 \, Re^{0,45}) \tag{3}$$

for hot-wires operated in air in the range 0.02 < Re < 44 produces
the best approximation.

The results achieved by King, Collis and Williams are applicable
to wires with a large ratio I/d, so that the heat dissipation can
be viewed as two-dimensional. For the hot-wires used in general with
a ration I/d in the order of magnitude of 100, the heat dissipation
through the wire mounting makes itself felt, whereby a direct cali-
bration becomes necessary.

It is true for the thermal state of equilibrium that the heat
loss Q of the hot-wire has to be equal to the supplied electrical
input, thus $I^2 \cdot R$.

What is interesting more than anything else from the aspect of anemometry is the relationsip between the particle velocity and the electrical input. This relationship can be expressed for hot-wire and hot-film probes at a certain overheating ratio in a given flow medium with constant temperature by the equation:

$$\frac{r\,R}{R-R_0}I^2 = A + B\,U^n,$$

(4)

with A, B and n being constants.

The output voltage of an anemometer is accumulated at a bridge circuit, the square of this voltage is proportional to the heat loss of the wire at the respective velocity.

Diagrams 2 and 3 show typical calibration curves of a hot-wire and hot-film transducer, respectively.
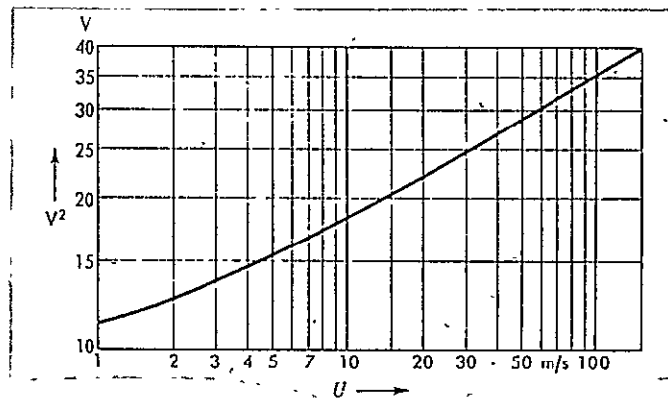

Diagram 2. Calibration curve of a constant temperature anemometer (DISA type 55D01) in air with a hot-wire transducer of the type 55A22. V bridge voltage, U flow velocity, approached curve $V^2 = 5.9 + 5.2\ U^{0.38}$

Diagram 4 shows schematically the most common calibration methods.

2.2. Dynamic properties of probes

To be able to describe the behavior of the hot-wire to time changes in the flow velocities, equation (4), determined empirically, will have to be supplemented for dynamic actions by an additional term considering the thermal inertia of the wire.
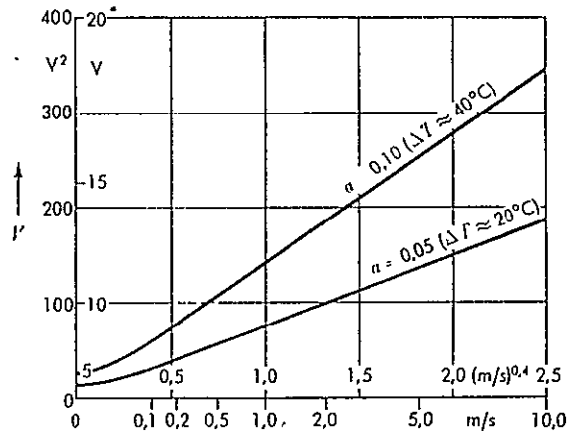
4

Diagram 3. Calibration curve of a constant-temperature anemometer (DISA type 44D01) in water with a hot-film transducer of the type 55A81 at two different overheating ratios a. V bridge voltage, U flow velocity.
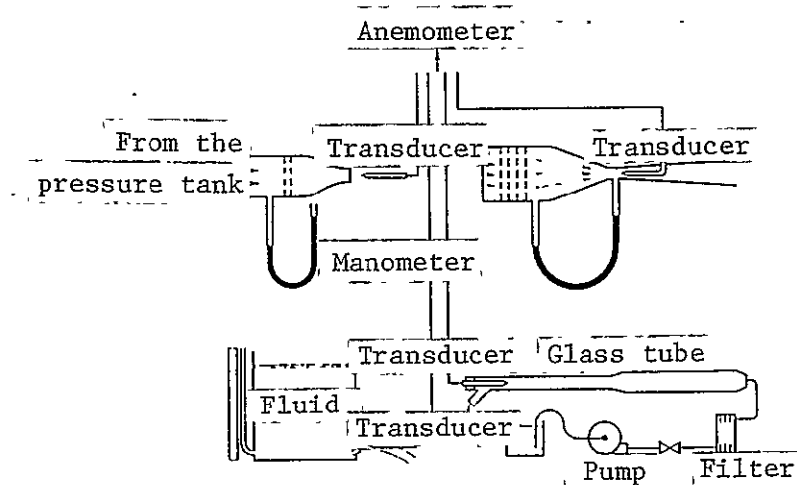

Diagram 4. Schematic representation of the most common calibration methods.

Assuming a uniform temperature distribution along the wire, we obtain

$$\frac{R}{R-R_0}I^2 = A + B(U)^n + \frac{C}{R-R_0}\frac{\mathrm{d}R}{\mathrm{d}t};\qquad (5)$$

In this

$$C = \frac{C_w}{\alpha R_0}$$

is the modified heat capacity of the wire.

In the following discussion of the modes of operation of a hot-wire, we shall return to this equation (5).

The first and simplest mode of operation is the heating of the wire with time constant-current from a constant-current source with high internal resistance. The change in resistance caused by cooling or the voltage loss at the wire is then a gauge for the flow velocity. In the second method the wire temperature is kept constant, with the heating current changing with the velocity. The third, known as the method of the constant-overheating ratio, uses two wires. This special technique is applied then, whenever the velocity changes are attended by temperature changes. At a constant-overheating ratio in relation to the temperatures of the flow medium, the probe then responds to only velocity changes.

Returning to equation (5), the dynamic behavior of the wire at a constant-heating current is to be considered now.

The instantaneous wire resistance is composed of two parts. The long-time mean value is to be marked by a bar and the time variable value by a small letter:

$$R = \bar{R} + r$$
$$U = \bar{U} + u \tag{6}$$

By insertion into equation (5), the following differential equation is obtained for resistance changes:

$$\frac{dr}{dt} + \frac{R_0 (A + B(U)^n)}{\bar{R} C} r = - \frac{B n (\bar{U})^{n-1} (\bar{R} - R_0)}{C} u. \tag{7}$$

This differential equation of the first degree is characterized by the time constant:

$$\tau = \frac{\bar{R} C}{R_0 (A + B(U)^n)}. \tag{8}$$

Hence, if the wire for example is subjected to a sudden rise in velocity, then the wire resistance drops and assumes a new value on an exponential curve. As a result the time constant is proportional to the heat capacity and to the resistance ratio of the wire and

decreases with rising flow velocity (hereto see also Diagram 5).

The dynamic characteristic can be described in addition by the behavior with sinusoidal changes of the flow velocity, as is shown in Diagram 6.

Diagram 5.⁻ Pulse response of the hot-wire with a sudden rise of the flow velocity

The upper limiting frequency of a wolfram wire of 5 µm diameter amounts to about 500 Hz, whenever it is operated in atmospheric air at a resistance ratio of 1.8 and at a flow velocity of 100 m/s. This limiting frequency can be raised, however, several hundredfold by electronic aids.
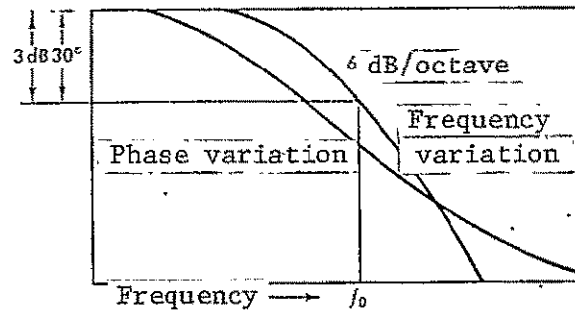
Diagram 6. Dynamic behavior of the hot-wire probes with sinusoidal velocity changes. Frequency and phase variation. Upper limiting frequency $f_0 = 1/2\pi\tau$.

The frequency variation of a hot-film probe (see Diagram 7) is strongly dependent upon the thermal properties of the carrier material. The thermal inertia of the thin platinum film even with a thickness of about 100 Å is negligible on the other hand.
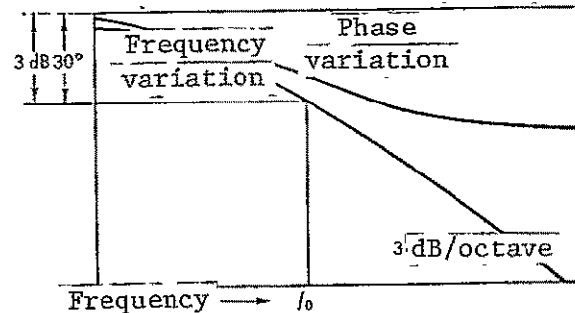
Diagram 7. Dynamic behavior of the hot-film probes with sinusoidal velocity changes in gases. Frequency and phase variation f_0 upper limiting frequency.

A sinusoidal change of the hot-film temperature causes a strongly attenuated temperature wave in the surface of the carrier material. The wavelength is many times over larger than the skin effect which is of the following magnitude:
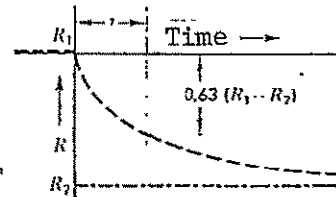
$$\delta \approx \sqrt{\frac{k_b}{\omega c_b}}.$$

(9)

The phase of the heat flow in the carrier material will lag the surface temperature as a result by an angle ϕ.

With Pyrex-glass as a carrier material we obtain $\overline{\delta} \approx 0.4 \sqrt{f}$ (f in Hz, δ in mm). The thermal boundary layer affects the frequency variation even at very low frequencies. For higher frequencies the attenuation amounts, however, to only 3 dB/octave, and the phase shift approaches 45°.

3. Electronics of the Anemometer

The electronic part of the anemometer is to enable the stable operation of the probe and to expand its properties, above all relating to the frequency variation.

3.1. Constant-current operation.

In the constant-current operation of a Wheatstone bridge, in the one branch of which the transducer is located, is fed from a current source in series with an adjustable resistance. The series resistance is to be as large as possible compared to the total resistance of the bridge in order that the same current always flows through the network.

The voltage resulting at the vertical diagonal of the bridge is then a gauge for the flow velocity.

For the velocity components above the limiting frequency of the transducers there is produced an amplitude drop of 6 dB/octave, /R 2 and the phase of the output signal will lag with an angle $\varphi = \arctan \omega \tau$ compared to the actual flow action. The frequency variation is characterized, however, by a single time constant and can be compensated, therefore, by a simple RC-member which increases the amplification for higher frequencies.

Diagram 8 shows the block circuit diagram of a constant-current anemometer with a compensation network and an additional amplifier.
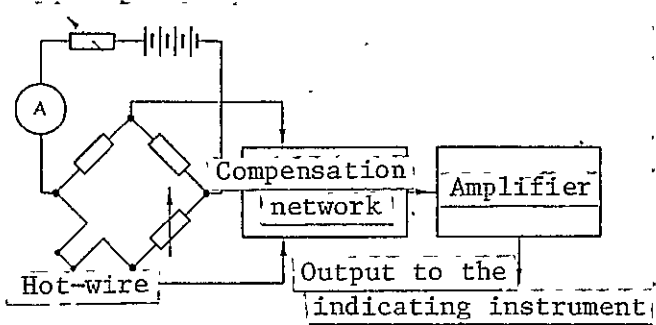
Diagram 8. Principle circuit diagram of a constant-current anemometer.

With the time constant of the transducer corresponding to equation (8) depending upon the mean flow velocity, the compensation network has to be re-adjusted with a change of the latter.

The frequency variation of a hot-film probe can not be characterized by a single time constant. It would be very difficult to realize a compensation amplifier like the probe with opposite properties; for that reason, hot-film transducers are practically not used in the constant-current operation.

3.2. Constant-temperature operation

This mode of operation offers basic advantages in operation in regard to accuracy and simplicity, but more than anything else it is practicable, too, for large velocity fluctuations.

The fundamental idea of this mode of operation consists of reducing the affect of the probe's thermal inertia by keeping the sensing element always at a constant temperature (resistance) and using the necessary heating current for it as a gauge for the velocity.

This principle was proposed by Kennelly [3] previously in 1909; of course the necessary highly developed electronic system could not be realized until much later. Its block circuit diagram is depicted in Diagram 9.

In the state of equilibrium a certain voltage lies at the vertical diagonal of the bridge which is delivered by the servo amplifier. If the convective cooling at the probe is altered, then a small voltage will result at the
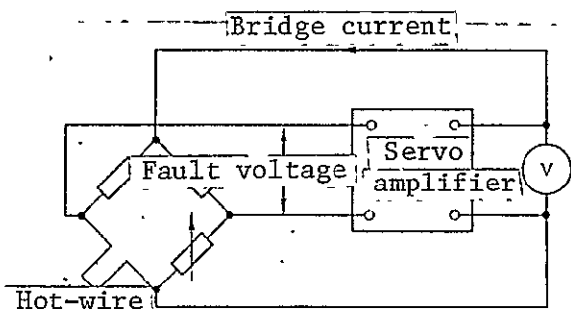

Diagram 9. Principle circuit diagram of a constant-temperature anemometer.

9

horizontal diagonal which — amplified many times — is coupled
back to the vertical diagonal. Consequently the polarity of this
coupled-back voltage is selected in such a way that the bridge bal-
ances automatically, and it can be shown [4], that by this the upper
limiting frequency is increased by the factor

$$g \approx 2\,a\,RS$$

With this $a = (R - R_0)/R_0$, is the overheating ratio and S the gradient
of the servo amplifier.

Because of the inclination to high frequency oscillations in
a closed loop of this kind, it is found difficult to expand the
frequency range by enlarging the gradient of the amplifier, as this.
too is known from control engineering. The art of constant-temperature
anemometry lies consequently in the design of a stable controlled
system with high loop amplification. '

The amplification of the DISA-constant-temperature anemometer of
the type 55D01 can be adjusted, for example, in 11 stages from 150 to
5000, with a maximum upper limiting frequency of 400 kHz in the bridge
ratio 1:1 (active to inactive branch) and 150 kHz in the bridge ratio
1:20 being produced with a standard hot-wire probe.

While the bandwidth is limited by the spatial resolving of the
probe in measuring turbulence, the large bandwidth of the system
reduces, nevertheless, phase shifts and can be used to advantage in
measuring spasmodic passing flow actions, as for example in impulse
wave tubes.

4. Applications

In general the probe will respond to every change of heat dissi-
pation. This can be caused for example even by a change of temperature
or pressure of the flow medium. Although even these magnitudes can
be measured with the aid of the anemometer, only applications in ane-
mometry are to be considered in the following.

10

4.1. Measurements of the mean flow velocity

The basic non-linear relationship between flow velocity U and output voltage V, given by the equation

$$V^2 = A + BU^n,$$ (10)

can be linearized electronically, for example, by an analog computing element with the transmission characteristic

$$V_{out} = k(V_{in}^2 - V_{in_0}^2)^m.$$ (11)

With $V = V_{in}$,

$$V_{in_0}^2 = A, \quad m = \frac{1}{n}$$

we obtain from the two equations:

$$V_{out} = K(A + BU^n - A)^{1/n} = KBU,$$ (12)

thus a velocity proportional output voltage.

Often we shall dispense with a linearization for stationary actions or for turbulence degrees under 10% and use the direct calibration curve.

4.2. Measurement of dynamic flow actions

With an ideal anemometer we would be able to measure at one point the instantaneous value of the flow velocity in three directions

Although these requirements are not completely met, the hot-wire /R 2 anemometer is still the best approach to this ideal, and practically the entire empirical knowledge on turbulence was gained with the aid of instruments of this kind.

Because of its large frequency range the hot-wire anemometer is particularly well suited for investigating [the] dynamic response of flow mechanical elements (Fluidies) which are used in pneumatic and hydraulic controlled systems.

Because of the small dimensions of transducers the boundary layer flows are disturbed only to a slight extent whenever a probe is brought in from without. In this manner, velocity profiles in boundary layers can be determined immediately.

Of course a correction becomes necessary [6] for wall clearances smaller than 0.2 mm as a result of a heat transfer to the wall.

With the aid of film transducers inserted flush into the wall it is likewise possible to measure the wall stresses [7].

The measuring procedure can be applied in gaseous and liquid media. For measurements in electrolytic conducting liquids (for example tap water) quarz-coated film probes come into question more than anything else.

4.3. Directional measurements

The hot-wire is dependent upon direction, and it has its maximum sensitivity with vertical incident flow. In the range $45° < \theta < 135°$ the ensuing effective velocity, for example, in equation (10) can be approximated by [5]:

$$U_{eff} = U \sin \theta \tag{13}$$

This effect can be used directly to advantage for stationary or periodic passing actions by locating the sharply pronounced minimum for directional measurements by twisting the probe.

So-called X-probes are used for static running off actions. These consist of two wires forming an angle of 45° with the mean flow direction and connected respectively to an anemometer. By adding or subtracting the instantaneous values of both output signals of the anemometers and formation of effective values, the velocity components can be determined then simply and directly for non-isotropic turbulence.

12

Other applications are not to be discussed here; however reference is made to the bibliography.

Appendix

Symbols used:

Q	Heat losses
T	Temperature of the heated transducer
T_O	Temperature of the ambient flow medium
R	Operating resistance of the heated transducer
R_O	Resistance of the transducer at ambient temperature
U	Flow velocity
V	Bridge voltage
V_{out}	Output voltage of the linearizer
V_{in}	Input voltage of the linearizer
V_{in_O}	Input voltage of the linearizer at 0 voltage output voltage
I	Probe current
S	Amplifier gradient
I_m	$(I \cdot I_0)2$ Mean temperature
R_c	$\frac{dU}{\nu}$ Reynolds' number
P_r	$\frac{\nu \rho c_p}{k}$ Prandtl number
P_c	$Pr \cdot Rc = \frac{dU_{\rho} c_p}{k}$ Péclét number!
C_w	$\rho_w c_w \frac{\pi}{4} d^2 l$ Heat capacity of the wire
a	$[(R - R_0)/R_0]$ Overheating ratio
d	Diameter of the wire
I	Length of the wire
c_w	Specific heat of the wire
c_b	Specific heat of the carrier material
c_p	Specific heat of the fluid at constant pressure
k	Heat conductibility of the fluid
k_b	Heat conductibility of the carrier material
r	Alternating component of the resistance
u	Alternating component of the velocity
f	Frequency in Hz
v	Kinematic viscosity of the fluid
ω	Circular frequency

13

δ	Skin effect
φ	Phase angle
ρ	Density of the flow medium
ρ_w	Density of the wire
λ	Temperature coefficient of the resistance
τ	Time constant
θ	Angle of rotation

References

1. King, L. V.: On the convection of heat from small cylinders in a stream of fluid. Phil. Trans. Roy. Soc., London (1914).

2. Collis, D. C. and Williams, M. J.: Two-dimensional convection from heated wires at low Reynolds' numbers. J. of Fluid Mechanics 6 (1959), pp. 257-284.

3. Kennelly, A. E., Wright, C. A., and Bylerelt, J. S.: The Convection of heat from copper wires. Trans. Amer. Instn. electr. Eng. (AIEE) 28(1909), pp. 363-396.

4. Andersen, O. K.: Time resolving property for correlation measurements with the hot-wire and hot-film anemometer type 55A01. DISA information No. 4, December 1966, published by DISA, Herlev, Denmark

5. Grant, H. P., and Dronauer, R. E.: Fundamentals of hot-wire anemometry. Symposium on measurement in unsteady flow. Mass. May 21-23, 1962, published by Amer. Soc. mech. Eng. (ASME).

6. Wills, J. A. B.: The correction of hot-wire readings for proximity to a solid boundary. J. of Fluid Mechanics, 12 (1962).

7. Bellhouse, B. J., and Schultz, D. L.: J. of Fluid Mechanics, 24 (1966), pp. 279-400.

Other literature without reference to this paper:

8. Hinze, J. O.: Turbulence, an introduction to its mechanism and theory. McGraw-Hill Book Company, Inc., New York, 1959.

9. Wehrmann, O.: Further development and modern applications of hot-wore metrology. Konstruktion, 13 (1961), pp. 183-186.

10. Rasmussen, C. G.: Air jet-hot-wire microphone. DISA information, No. 2 (1965).

11. Spangenberg, W. G.: Heat-loss characteristics of hot-wire anemometers at various densities in transonic and supersonic flow. NACA, T.N. 3381 (1955).

12. Korásznay, L. S. G., and Törmark, S. I. A.: Heat loss of wires in supersonic flow. Bumblebee Series, Report No. 127 (1950).

13. Wise, B., and Schultz, D. L.: Turbulence measurements in supersonic flow with the hot-wire anemometer. OUEL Report No. 83 (1955).

14. Vrebalovich, T.: Application of hot-wire techniques in unsteady compressible flows. Proc. Symp. on measurement of unsteady flow. ASME (1962).

15. Korásznay, L. S. G.: The hot-wire anemometer in supersonic flow. J. of the aeronautical Sci.,117(1960), p..565.

16. Korásznay, L. S. G.: Turbulence in supersonic flow. J. of the aeronautical Sci. 20 (1953), 10, p. 657.

17. Morkorin, M. V.: Fluctuations and hot-wire anemometry in compressible flows. AGAR Dograph 24(1956).

18. Laufer, J., and McClellan, R.: Measurement of heat transfer from fine wires in supersonic flows. J. Fluid. Mech., 1 (1956), p. 276.

19. Morkorin, M. V., and Phinney, R. E.: Extended application of hot-wire anemometry to high-speed turbulent boundary layers. AFOSR TN 58-469, John Hopkins Univ., Dept. of Aeronautics (1958).

20. Bellhouse, B. J., Schultz, D. L., and Karatzas, N. B.: The measurement of fluctuating components of velocity and skin friction with thin-film heated elements with application in water, air and blood flows. Oxford Univ. Rep. No. 1003(1966).

21. English, J., Hetcher, B., and Steckelmacher, H.: A wide-range constant-resistance Pirani gauge with ambient temperature compensation. J. sci. Instrum. 42 (1965), pp. 77-80.

22. Bomelberg, H. J.: Miniature hot-wire pressure gauges for wind tunnel work. Report No. 1095, Ballistic Research Lab, Maryland USA (1960).

23. Sandborn, V. A.: A hot-wire vacuum gauge for transient measurements. Air Force Bal. Syst. Div. USAF (1963). AVCO Corporation, Silmington, Mass.   /R 22

24. Wills, J. A. B.: A traversing orifice-hot-wire probe pair for use in wall pressure correlation measurements. National Physical Laboratory (NPL) Acro Rep. 1155(1965).

25. Remenyik, C. J., and Korásznay, L. S. G.: The orifice-hot-wire probe and measurement of wall pressure fluctuations. The John Hopkins Univ.

26. Chao, J. L., and Sandborn, V. A.: A resistance thermometer for transient temperature measurements. Mech. Paper No. 1, Colorado State Univ. (1964).

27. Glick, H. S.: Thin-film bolometer. Rev. sci. Instrum. 33 (1962),
     pp. 1268-1276.

28. Baldwin, L. V., and Sandborn, V. A.: Hot-wire calorimetry: theory
     and application to ion rocket research. NASA Techn. Report R 98
     (1961).

29. Oertel: Strossrohre, Wien, New York: Springer-Verlag 1966.

30. Dosanjh, D. S.: Studies of transient hot-wire response in a shock
     tube. John Hopkins Univ. Dept. Aeronautics Rep. CM 725(1955).

31. Oertel: Hot-wire measurement of a change of density of the flow
     of mass in a weak compression shock. LRSL. Technical Report 1a
     (1956).

32. Champagne, F. H.: Turbulence measurements with inclined hot-
     wires. Boeing Scientific Research Laboratories, Flight Sciences
     Laboratory, Washington, Report No. 103, Dec., 1965.

33. Wehrmann, O.: Methods and applications of hot-wire metrology
     for flow actions. Konstruktion 10(1958), pp. 279-307.

34. Berger, E., Freymuth, P., and Froebel, E.: Application of con-
     trolled engineering for the development of a constant-temperature
     hot-wire anemometer. DVL-Report No. 282(1963).

35. Freymuth, P.: Feedback control theory for constant-temperature
     hot-wire anemometers. Rev. sci. Instrum. 38(1967), 5, pp.
     677-681.