Investigation on Characterizing Heated Pulsating Flows with Hot Wire Anemometers - A Hands-On Approach

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DOI: 10.13111/2066-8201.2014.6.2.9

Abstract: *The pulsating heated flows are traditionally a difficult subject to treat with conventional hot wire or film methods. Special factors that complicate matters are flow reversal and non linear flow effects of vortices and wire probe wake disturbances on the heat transfer to the hot film or wire sensor in heated pulsating flows. The presence of these strongly nonlinear and unknown terms leads to great difficulties in calibration of hot film probes in this particular regime. The paper analyses the current state of matters in the field and reports a series of solutions that have been practically tested in a case of a high speed pulsated heated flow. Normally such measurements are made in a non-contact fashion using a LDV system or various visualization techniques but there have been recent attempts to use a constant temperature hot wire anemometer system (CTA).To obtain meaningful calibration for hot wire films in hot pulsating flows, a comparison system on other principles (LDV) was used, as well as a specially designed nozzle to replace the calibrator unit that could not be operated with heated fluid due to structural integrity reasons. The method as described below works well for the expected speed range that could be generated using the special nozzle.*

Key Words: *Hot wire anemometer, pulsated heated flow, experimental method*

1. GENERAL CONSIDERATIONS ON HOT WIRE ANEMOMETRY

Hot wire anemometers are fast and accurate simple instruments meant to measure cold flow velocity. The probes they use can be small and the frequency response is good enough that high frequency velocity fluctuations can be detected. Their traditional use is to measure mean velocity and turbulence intensity in cold flows. Other uses such as measuring pulsated flows [1] or heated flows, or even worse, heated and pulsating flows [2], [5], [6] can be attempted with varying degrees of success but results are marred by errors intrinsic to the measurement method and corrective post processing along with special experimental setup must be undertaken to try and minimize these errors. Heated flows pose a challenge because anemometers calibrated to run at a certain temperature interpret any change in flow temperature as a change in velocity, unless special measures are taken. Manufacturers show formulae in catalogs that can compensate for temperature drifts that affect probe resistance but as it becomes obvious in the case of heated flows, the method is only effective up to 40^{o}C or less [2], [6]. There are results [6] that can be applied to heated flows up to 550 K, using a hot wire CTA calibrated at room temperature, but only for low speeds and mass flows, with little to no flow reversal.

The problem of measuring pulsed heated flows is a particularly difficult one when using Constant Temperature Anemometers (CTA) with classical thermal compensation (RTD or thermocouple along with heat-resistivity relation given by (1) due to factors linked to a poor heat transfer compared to a steady jet of the same mass flow and maximum velocity [1], vorticity induced thermal transport and the clearly non-adiabatic characteristics of the flow [2], and to the fact that convection cooling on the hot film or wire probe is not direction – aware [3]. It also becomes obvious that a CTA system can only operate correctly if these assumptions are correct: a). velocity impinges normally and is uniform across the wire; b). fluid temperature and density remain constant c). flow has a low speed compared to the speed of sound d). the Nusselt number is constant. These assumptions are not valid in a heated pulsating flow.

The resistance of the probe in heated flows is considered by most CTA systems to vary according to the resistivity-temperature law given by:

$$R_{crt} = R_{tref} + \alpha\left(T_{crt} - T_{ref}\right) \tag{1}$$

where: R_{crt} is the probe resistance at a given working temperature,

R_{tref} is the probe resistance at some reference temperature-usually given by manufacturer and used as reference point,

α is the temperature coefficient that affects the resistivity of the metal of the hot film or wire probe, also specified by probe manufacturer,

T_{crt} is the probe working temperature (in the heated flow),

T_{ref} is the reference temperature at which the probe resistance R_{tref} is given by the probe manufacturer.

The real problem is that in the case of large speed fluctuations with flow reversal the resistivity only changes with perceived cooling- that is disconnected from flow velocity by effects such as modified (worsened) heat transfer from air to probe caused by heated air vortices that form in the wake of the probe and orientation changes in the flow that still cool the wire or film probe as a steady flow having a fixed speed equal to the maximum amplitude of oscillation would do. In [3] authors argue that using simple uncorrected CTA for pulsed flows (as opposed to small fluctuation flows) -even in cold flows- is wrong and show that problems arise due to the fact that while a CTA is not affected by thermal inertia of the wire because it keeps the wire temperature constant, it remains a third order system and harmonics appear in the system's response to oscillating input. CTAs are tuned to achieve optimal bandwidth at a certain mean speed, and large departures from it are likely to cause system instability and signal distortions. This means that for pulsating flows, the probe resistance can no longer be held constant. The operating principle of CTA is negated by these pulsating flow conditions.

The conclusion of Berson et al. in [3]: to date no procedure is available to correct nonlinearities in commercial CTAs in pulsating flows. Moreover, if any flow reversal occurs anywhere in the flow, the heat transfer and the flow speed are no longer connected by any working law, so that there is absolutely no way to measure reversing pulsating flows with hot wires. The paper [3] shows that the CTA output contains harmonics not present in the input. For lower frequencies some compromise can be made as long as the turbulence in the probe wake is not too large. Berson states that for high frequency velocity measurements in pulsating flows even without flow reversal, the only relevant solution is adequately corrected CVA (Constant Voltage Anemometer).

The latter fact shows that in highly turbulent flows with large fluctuations in speed or in multiple pulsating jets functioning close to one another, the measured CTA speed contains components not directly linked to flow conditions. Probe geometry and probe-nozzle interactions are also to be taken into account whenever the probe head needs to be in close proximity (d< probe head diameter) to the exit nozzle for the pulsating jet and even more so when the probe diameter is close to the diameter or relevant dimension of the said exit nozzle [5].

2. INNER WORKINGS OF HOT WIRE ANEMOMETERS AND THEORETICAL FOUNDATION OF INTERPRETING DATA

Let us analyze the classical theory on hot wire probes. A hot wire anemometer, regardless of type, works by heating a small wire probe and exposing this heated filament or film to the flow. This has the effect of cooling down the wire and thus modifying its resistance. Here is where the constructive principles diverge: CTA - Constant Temperature Anemometer- has a circuit that tries to keep the hot wire at the same temperature, regardless of the flow, and measures the needed heating current that is supplied to achieve this; the CVA - Constant Voltage Anemometer tries to keep the voltage drop across the wire constant, and CCA - Constant Current Anemometer - tries to keep the current flow through the wire constant.

Let us analyze the energy balance of a hot wire in a flow, taking into account the thermal inertia of the wire (it is noteworthy that a CTA tries to keep wire temperature constant and thus is not directly affected by thermal inertia of the wire - except when the pulsating flow has large deviations from the mean value of speed).

$$\frac{m_w c_w}{\alpha R_0}\frac{dR_w}{dt} = I_w^2 R_w - \left(R_w - R_a\right) f\left(U\right) \tag{2}$$

where: m_w is the probe's wire mass,

C_w is the probe's wire heat capacity,

R_w is the wire resistance dependant on wire temperature, $R_w = R_w(T_w)$,

I_w is the current through the wire,

R_a is the resistance of the wire at the ambient temperature,

R_0 is the wire resistance at a given temperature T_0 and is a probe manufacturing constant.

$f\,(U)$ is the heat transfer from the wire to the flow, depending on flow speed U.

Equation (2) simply states that the energy transfer from the hot wire to the flow for an infinitely long wire having a thermal inertia is given by the portion of the Joule heating energy that is transferred to the surroundings by convection, conduction and in a much smaller part by radiation, and that heat transfer is dependent on flow speed U.

If we look further into classical assumptions on hot wire theory, we can see why it fails for pulsating flows: because the convective term can be written as:

$$\left(R_w - R_a\right) f\left(U\right) = Q_c = NuA(T_w - T_a) \tag{3}$$

where: Q_c is the convective heat flux,

Nu is the Nusselt number,

T_w is the hot wire temperature,

T_a is the ambient temperature.

It is the classical assumption that if the speed changes, the convective heat transfer coefficient changes and the hot wire will reach a new equilibrium so that we have a quasi-static heat transfer in this state, described as:

$$Q_J = Q_C \Rightarrow I_w^2 R_w = hA(T_w - T_a) \tag{4}$$

That translates to: when the wire is at thermal equilibrium, Joule heating equals heat transferred to the flow.

Q_j is the Joule heating,
h is the film coefficient of heat transfer,
A is the heat transfer area (the hot wire lateral area or hot film area),
T_w is the hot wire or film temperature,
T_a is the ambient temperature of the flow.

Typically, heat transfer is made from the hot wire to the stream through a thermal boundary layer (TBL) that is characterized by a convection (or film) coefficient designated h. Newton's Law of Cooling models heat transfer through the TBL:

$$q'' = h(T_\infty - T_s) \tag{5}$$

where: q'' = heat flux or rate of heat transfer per unit area (W/m^2)
h = convection (film) coefficient (W/m^2 K),
T_∞ = average temperature of the fluid stream,
T_s = surface temperature of the pipe or wall on which the stream flows.

And finally:

$$I^2 R_w = Nu * k_f \, / \, dA(T_w - T_a) \tag{6}$$

Assuming a forced convection due to flow on the probe, we get:

$$Nu = A_1 + B_1 * \mathrm{Re}^n = A_2 + B_2 * U^n \tag{7}$$

Where A is a natural convective term, $B*U^n$ is a forced convection term, and U is the speed of the flow, and thus we get the well-known King's law for general hot wire probes:

$$I_2 R_w = E_{bridge}{}^2 = (T_w - T_a)(A + B * U_n) \tag{8}$$

E_{bridge} is the voltage used as a measure of flow speed, assuming all prior assumptions were correct.

A, B and the exponent n are undetermined coefficients, and empirically fitted to data. All the calculations are made for infinite wire lengths. Typically for an infinitely long cylinder B is constant and A is the voltage squared at zero velocity, as shown e.g. in [7]. Taking all of this into account, it becomes apparent that an individual calibration is to be made for each actual, finite length wire probe every time before a test, and that the calibration has to be made at the same temperature as that of the test, by virtue of preserving the film coefficient of heat transfer among other things.

3. CONSIDERATIONS ON CORRECTIONS TO BE APPLIED FOR HEATED PULSATING FLOWS AND FURTHER INVESTIGATIONS

We must pause to ponder the following: at constant temperature or at low temperature variations, h, the film coefficient of heat transfer can be considered a material constant. In fact it is a highly nonlinear function depending on temperature and Reynolds. For example, h for air at 300 K is 0,0262 W $m^{-1}K^{-1}$ while for heated air at 600K it is 0,0457 W $m^{-1}K^{-1}$. In pulsed flows with large deviations from the mean velocity, h is no longer constant so Newton's law of cooling does not hold true here; pulses create turbulence that worsen the heat transfer surrounding the wire probe with vortices and impeding heat transfer; heated flow pulses exchange heat through fluid boundaries and interactions and thus h is always varying. Moreover, if the flow has large deviations from the mean- reaching zero m/s before increasing again to maximum following a sinusoidal law a thick turbulent layer is created around the probe, not allowing for any thermal equilibrium to occur.

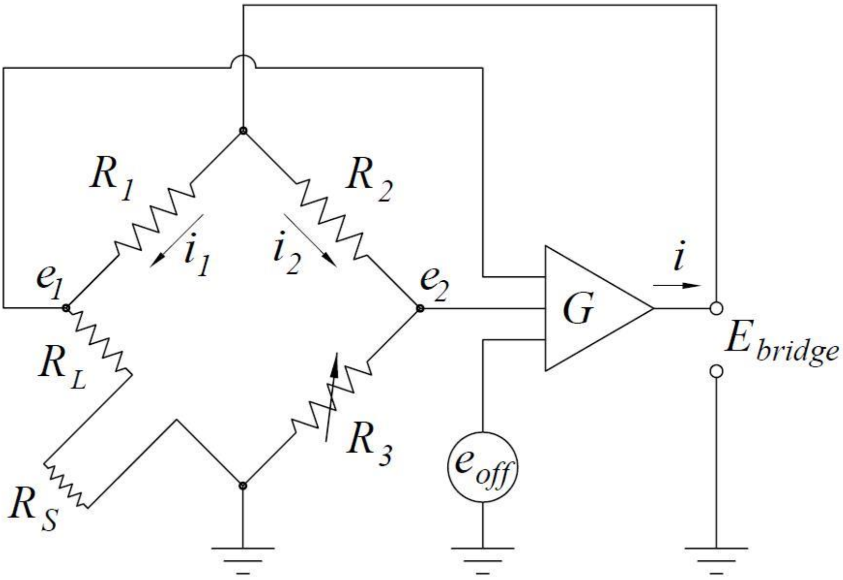

Figure 1. The Constant Temperature Anemometer. (CTA) [7]

It becomes apparent that we can no longer assume the operation of the anemometer between stabilized states as equilibrium is never quite reached due to the constant changes in the turbulence.

Let us analyze the necessary modifications to standard theory allow the use of a hot wire anemometer in hot pulsating flows. As we have previously seen, the main problems are a non constant film coefficient for heat transfer from the probe to the flow, caused by increased turbulence, and thermal compensation problems due to the high temperature of the flow. Newton's law of cooling cannot apply and King's law is poorly fitting the experimental data, as seen in [6].

The dynamic viscosity of the air also changes with temperature, as it is apparent from Sutherland's formula:

$$\mu = \mu_0 \frac{T_0 + C}{T + C} \left(\frac{T}{T_0} \right)^{\frac{3}{2}} \tag{9}$$

which holds true for 0<T<555 K and where C is the Sutherland constant (120 K for air), T_0 is an established reference temperature for the gas (291,15 K for air), μ is the dynamic viscosity at temperature T and μ_0 the dynamic viscosity at temperature T_0.

Two correction factors taking into account the changes in temperature and fluid properties are possible for King's Law (7), but as shown in [6] only the first one is important: the ratio of temperature drop from the hot wire T_w to the flow temperature T_x to the temperature drop from the wire temperature T_w to ambient reference temperature $T_{0.}$

$$CF = \frac{T_w - T_x}{T_w - T_0} \tag{10}$$

For small speeds and high temperatures, good results have been obtained by using (10) together with (7), with an n coefficient equal to 0, 55.

The correction for the voltage takes the shape of:

$$V_c = V_m \left[\frac{(T_w - T_0)}{T_w - T_x} \right]^{0,55} \tag{11}$$

and is theoretically a curve fitting on King's law but validation was made only for low speeds pulsed heated flows.

Another possible path is to use a cold wire resistance thermometer together with the hot wire setup (in CCA mode) to allow for efficient temperature corrections. A constant current anemometer has a linear characteristic; as the CCA bridge maintains the current constant, it follows that the wire voltage will be proportional to the wire resistance that is in turn linked to the wire temperature. The current, set by the operator, should be small enough to neglect velocity fluctuations but large enough to give a fair temperature resolution.

A simpler solution (with some inconvenient aspects) is using a hot flow similar to that to be measured and another measurement principle, a self-calibrating Laser Doppler Velocimeter. This equipment, due to its operating principle, is considered a good reference to characterize flow without contact and with minimal disturbance (most authors say "no disturbance" but forget the required seeding of the flow that produces some -albeit minor- changes).To solve the problem of calibrating hot wires for high speed flows, a solid wall strong pipe nozzle was built and used to pass heated non pulsating flow at different settings, and the exit from the CTA probe was recorded. The speed was also directly measured using the LDV and thus a direct calibration for heated flows could be carried out. The method eliminates the necessity of high performance temperature compensation but it is still under investigation as a means of measure for pulsating flows.

Although it could be adiabatic, a pulsed heated flow temperature varies during different stages of mass transfer. It can be considered for most non reversing pulsating heated flows that a "top hat" mass flow occurs. Associated with this mass transfer, the heat transfer is thought to follow a similar variation. This variation is currently the source of most errors in measurements in hot pulsated flows and is investigated to determine the necessary correction to minimize its effects.

4. CONCLUSIONS

Hot wire anemometers are useable in hot pulsating flows only when applying the required corrections to data. Directly read data are of little significance amplitude-wise, but can still convey a good image of the frequency spectrum or power distribution on the components of the flow. No single accurate and precise method exists to date for correcting hot wire anemometer speed data collected from pulsed flows with high velocities, but there are a number of promising techniques to be tried, some showing a very good concordance with experimental data collected by other means (LDV, etc.).

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