TRANSITION THERMAL PROCESSES IN VIBRATING WIRE MONITORS*

Arutunian S.G.[1], Decker G.[2], Mailian M.R.[1], Rosenbaum G.[3]
[1] Yerevan Physics Institute, Armenia
[2] Argonne National Laboratory, Argonne, IL 60439 USA
[3] University of Georgia, Athens, GA 30602 USA

Abstract

Dynamic characteristics of vibrating wire monitors (VWM) strongly depend on the media where the wire oscillates, and also on the geometry and materials of the wire and VWM housing. On the basis of a one-dimensional model of heat transfer along the wire, the time characteristics of transition processes of thermal equilibrium profiles are defined for wires of different materials and geometry. To decrease the response time of the VWM, a new scheme of measurement with constant mean temperature is suggested. In addition to the flux of particles/radiation deposited on the wire, the additional DC current maintains a constant wire oscillation frequency. The value of DC current serves as measure of particles/radiation flux.

INTRODUCTION

The first measurements of a hard X-ray undulator beam at the APS with a Vibrating Wire Monitor (VWM) [1] showed that the VWM is well-suited to neutral beams such as x-rays. Here we discuss the dynamic characteristics of the VWM depending on wire and housing materials. The measurements of convection heat sink parameters in air and hydrogen at different pressures are done. A new modification of the VWM with Tungsten wires and enlarged aperture is presented.

VWM DYNAMIC CHARACTERISTICS

In case of permanent photon flux falling on the wire, the equilibrium temperature profile along the wire is determined by the balance between the heat deposited on the wire and heat dissipation occurring in three ways: thermal conductivity along the wire, heat radiation and convective heatsink (in gas media). A change in mean wire temperature results in a change of wire strain, which is registered by measurement of the wire's natural oscillation frequency.

The temperature distribution $T(t,z)$ along the wire is determined by the heat conductivity equation:

$$c\rho\frac{\partial T}{\partial t} = \frac{\partial}{\partial z}\left(\lambda\frac{\partial T}{\partial z}\right) + q - R - A. \qquad (1)$$

Here c is the coefficient of heat capacity, ρ is the density, and λ is the coefficient of heat conductivity of the wire material, σ is the Stefan-Boltzman constant, q is the density of the deposited heat from all sources, $R = 2\varepsilon\sigma(T^4 - T_0^4)/r_w$ - heat sink by radiation, ε – emissivity factor, $A = 2\alpha_{conv}(T - T_0)/r_w$ - heat sink by convection with factor α_{conv}, r_w. – wire radius. T_0 - housing temperature. The power flux deposited on the wire is set $P = P_0\exp\left(-z^2/2\sigma_z^2\right)$, where σ_z is the width of the bunch. In this case $q = 2A(z)P/\pi r_w$ ($A(z)$ is equal 1 in VWM aperture and 0 elsewhere). If through the wire passes current a I_0 a term $I_0^2\Omega/\pi^2 r_w^4$ must be added to the q (Ω is the wire resistivity).

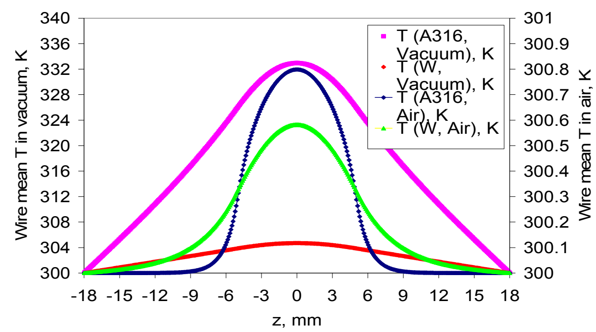

Fig. 1. Temperature profile along the wire for Stainless Steel and Tungsten in vacuum and air.

Results of calculations are presented in Fig. 1 (profiles for Stainless Steel and Tungsten in vacuum and air with heat sink factor α = 380 W/m/K, σ_z = 5 mm, P_0 = 1 mW/mm^2, VWM aperture 5 mm). It is seen that without convective heat dissipation the profiles are almost triangular. The largest overheating is revealed for Stainless Steel in vacuum.

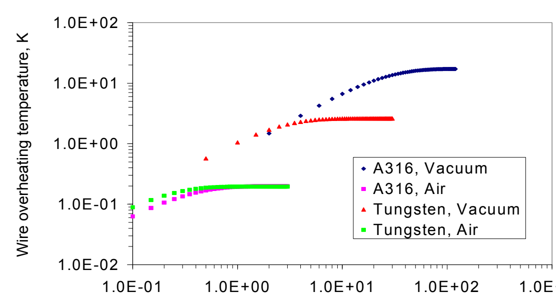

Fig. 2. Dynamic characteristics of temperature profile stabilization. Temperature in the center of the wire is presented.

* Work supported by U.S. Department of Energy, Office of Science, Office of Basic Energy Sciences, under Contract No. DE-AC02-06CH11357, and by Bergoz Instrumentation, Saint Genis Pouilly, France.

Fig. 2. represents the graphs of temperature dynamics in the wire center. For Stainless Steel in vacuum, due to a small coefficient of thermal conductivity (16.3 W/m/K) the temperature stabilization time is a few minutes (with accuracy of about 0.001 ^{0}C).

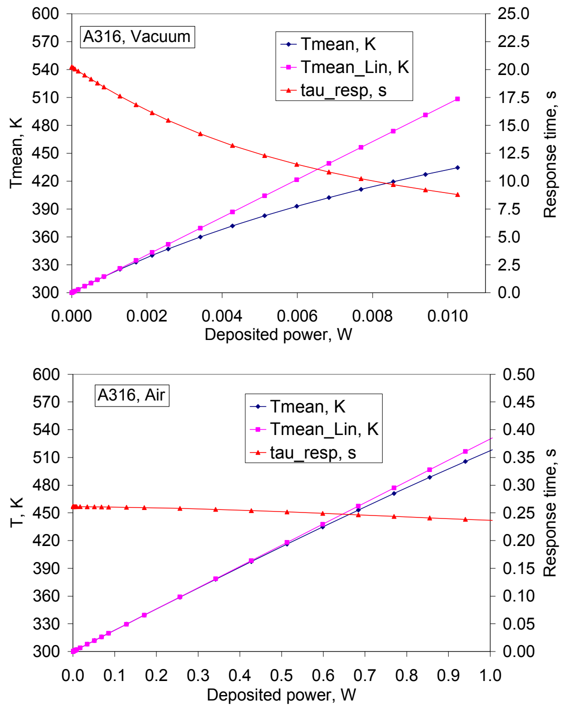

Fig. 3. Parameters of VWM with Stainless Steel wire in air and vacuum.

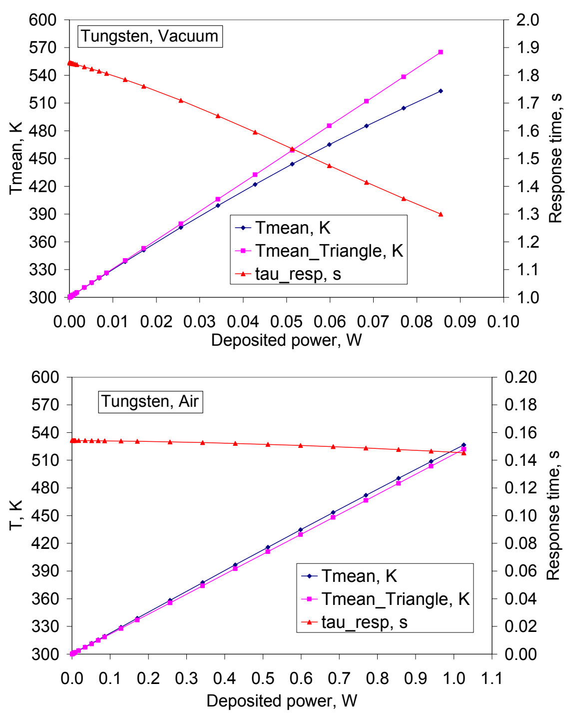

Fig. 4. Parameters of VWM with Tungsten wire in air and vacuum.

For practical applications it is important to determine dependence of wire mean temperature on the deposited power and dependence of the wire oscillation frequency on its temperature. The temperature profiles of Stainless Steel and Tungsten wires are calculated for different levels of power deposited on the wire. Results for Stainless Steel are presented in Fig. 3 and for Tungsten in Fig. 4.

For comparison, the graphs of linear dependence are calculated for a triangular model of temperature and linear approximation of radiation heatsink. A difference from linear dependence occurs owing to the fact that heat radiation is proportional to the fourth power of temperature, so that the portion of thermal loss due to radiation increases at high temperatures.

Summary characteristics of Stainless Steel (A316) and Tungsten wires are presented in Table 1.

Table 1

Material	A316 Vacuum	A316 Air	Tungsten Vacuum	Tungsten Air
$\Delta T_{mean}/\Delta Q$, K/mW	19.4	0.23	3.0	0.23
$\Delta F/\Delta T_{mean}$, Hz/K at F_0 = 4200 Hz	40.2	40.2	8.8	8.8
$\Delta F/\Delta Q$, Hz/mW	779.6	9.3	26.4	2.0
response time, s	20.2	0.26	1.8	0.15

We present useful formulas for the calculation of wire maximal overheat temperature ΔT_{MAX} and response time τ assuming a trianglular profile at room temperature.

$$\Delta T_{MAX} = \frac{q}{\pi d^2 l(\lambda / l^2 + 2\sigma_{SB} T_0^3 + \alpha_{conv} / 2d)} \qquad (2)$$

$$\tau = \frac{\rho c}{8(\lambda / l^2 + 2\sigma_{SB} T_0^3 + \alpha_{conv} / 2d)} \qquad (3)$$

Fig. 5. VWM with tungsten wires and enlarged aperture.

In Fig. 5 a new modification of VWM with two Tungsten wires and enlarged 8 mm aperture is presented.

The housing is made from AlN ceramic with a high value of thermal conductivity. This modification has a shorter response time and can be used both in vacuum and air. In the APS experiment [1], a VWM with two Stainless Steel wires and a 5 mm aperture was used.

CONSTANT TEMPERATURE VWM

Response of the VWM can be accelerated if instead of a "cold" wire a preheated wire is used. Such preheating can be done with an additional DC current [2]. As the photon beam heating varies, the DC current can be varied in order to maintain a constant frequency. This current is then used as a measure of photon beam heating. Note that such a procedure is used in so-called Constant Temperature Anemometers, see e.g. [3].

Let the Stainless Steel wire be heated by a current I = 20 mA (wire overheating is 19.1702 K). In this case, if the photon beam deposits P_0=0.7 mW/mm^2 onto the wire, the DC current I = 12.2033 mA results in the same mean wire temperature (see Fig. 6).

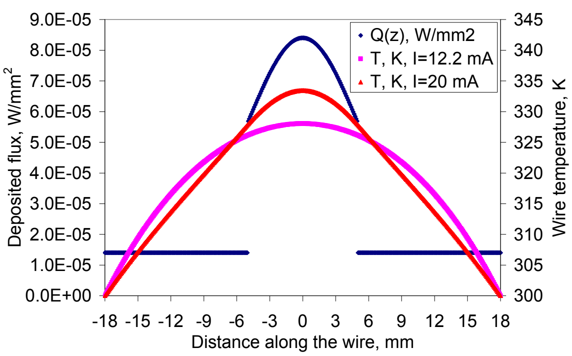

Fig. 6. Deposited power $Q(z)$ (DC current 12.2 mA and photon flux with P_0=0.7 mW/mm^2) and temperature profiles at DC currents 20 mA and 12.2 mA with photon flux.

In Fig. 7 we present the wire mean temperature dynamics from preheated state (DC current 20 mA) to the step photon flux 0.7 mW/mm^2 and DC current 12.2 mA (blue diamands). To compare we also present the dynamics from step photon flux 1.116207 mW/mm^2 that leads to the same temperature increment 19.1702 K. As one can see the same level of temperature close to the final increament is reached faster for preheated wire. E.g. the level 19.100 K is reached at 42th second for preheated wire and at 102th second for cold wire.

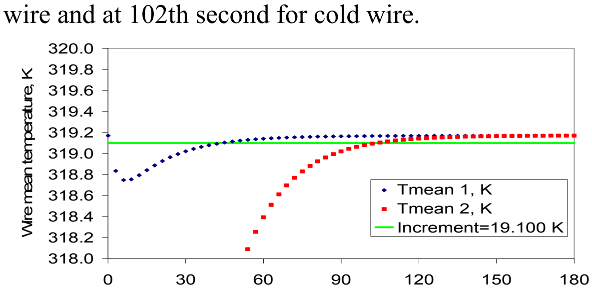

Fig. 7. Dynamics of wire mean temperature from preheated state (Tmean 1) and from cold state (Tmean 2).

CONVECTION FACTOR FOR VWM

Measurements of the convection factor for vibrating wires were performed at different pressures for air and hydrogen. This factor is determined by the properties of the heat sink surface, its location, the temperatures of the surface and surrounding media, and its consistency (see, e.g. [4]). For a vibrating wire the relative motion of the wire with respect to the media must also be taken into account. Experimental results are shown in Fig. 8.

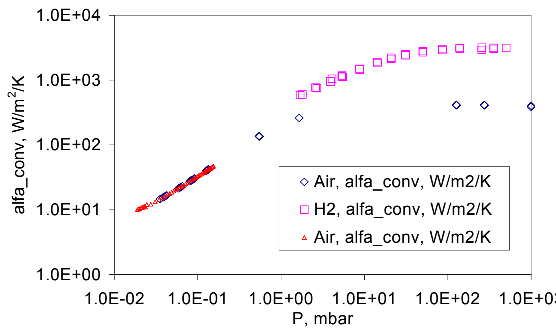

Fig. 8. Summary of convection factors for vibrating wires in air and hydrogen at different pressures.

The convective factor decreases sharply as the pressure is reduced below 1 mbar for air, and 10 mbar for hydrogen.. For hydrogen at normal pressure, this parameter is nearly an order magnitude larger than for air.

DISCUSSION

The response time of the VWM can be decreased in vacuum by using wires with a high thermal conductivity. Additional reductions in response time can be achieved by using the VWM in a gas media. As a consequence, however, the sensitivity of the VWM is decreased. Some decreasing of response time can be done also by constant temperature method. New modifications of the VWM with enlarged aperture and an AlN ceramic housing allows for more stable thermal conditions. This type of VWM can be further improved by using four wires. (two horizontal and two vertical).

REFERENCES

[1] G. Decker, S. Arutunian, M. Mailian, G. Rosenbaum. “First Vibrating Wire Monitor Measurements of a Hard X-ray Undulator Beam at the Advanced Photon Source”, these proceedings.

[2] Arutunian S.G., Dobrovolski N.M., Mailian M.R., Sinenko I.G., Vasiniuk I.E. “Vibrating wire for beam profile scanning.” Phys. Rev. ST Accel. and Beams, **2**, 122801 (1999).

[3] http://www.aoe.vt.edu/~simpson/aoe4154/hotwirelab.pdf.

[4] A.V. Yegorov. “Calculation of Power and Parameters of Electric Furnaces in Ferrous Metallurgy.” Moscow, 1990.