Pressure Gauge Filament for Neutral Gas Density Measurement using Alternating Current as Source Power

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Abstract: In plasma fusion research the in-vessel neutral gas density is often measured using hot cathode ionisation gauges which are modified for the application in high magnetic fields and for a measurement range between 10^{-3} Pa and 20 Pa. To obtain sufficient electron emission, the cathode (filament) is heated to high temperatures in the range of 1800 K by direct ohmic heating. To compensate for the induced Lorentz-forces, the filament must be relatively thick to provide sufficient mechanical stability which implicates increases of heating currents up to 20 A.

The heating current could be reduced by using a thinner filament in combination with alternating current with suitably chosen frequency to reduce mechanical stresses. The benefit of such a technique is besides saving of heating power, especially space-saving by applying thinner power supply cables. To estimate the suitability of such a solution a feasibility study by means of numerical methods has been carried out. The main subject of the investigation was the hot-filament for which alternating current has been used as power source. This paper provides first of all the main guidelines and features important in developing a pressure gauge filament heated by alternating current from the mechanical point of view.

Keywords: pressure gauge, filament, neutral gas, density measurement, plasma fusion, FEM

1. Introduction

The pressure gauge (PG) type reconsidered in this paper belongs to the hot-cathode or emitting-cathode ionization gauge category [1]. The measurement principle based on kinetic theory of ideal gas law, expressed in the form:

$$P = nkT \qquad (1)$$

where P [Pa] is the pressure, n [molecules/m^3] is the molecular density, k [erg/K] is the Boltzmann constant and T [K] is the absolute temperature. This is the fundamental equation on vacuum measurement, because it establishes a relationship between pressure and gas density. This measurement method is also called "indirect" since it measures the gas density via the strength of ionisation process and not directly the pressure. The hot-cathode or usually called filament is the key part of the PG equipment. The filament provides an electron emission current which ionises the surrounding gas and produces an ion current. Both currents are collected at electrodes kept at an appropriate electric potential. Naturally, the filament operating temperature is quite high, around 1800 K, and is heated by either DC or AC current. Although, the current source does not influence the measurement procedure, there are some advantages or disadvantages in the application and design. In case of DC driven heating, there is no risk of disturbance for surrounding equipment. The AC driven heating offers potentially lower Lorentz stresses in the filament if operated within a magnetic field, which in turn enables to use a thinner filament and thus lower heating power. On the other hand, a suitable frequency modulated AC source and possibly an electromagnetic shielding are needed.

2. Pressure gauge design

The geometry of the PG filament used in the analysis is based on the ASDEX Upgrade PG which operates with direct current [2]. Compared to other PGs, which work with a similar principle, the PG developed at IPP (Fig. 1) differs mostly in the "linear" electrode arrangement.

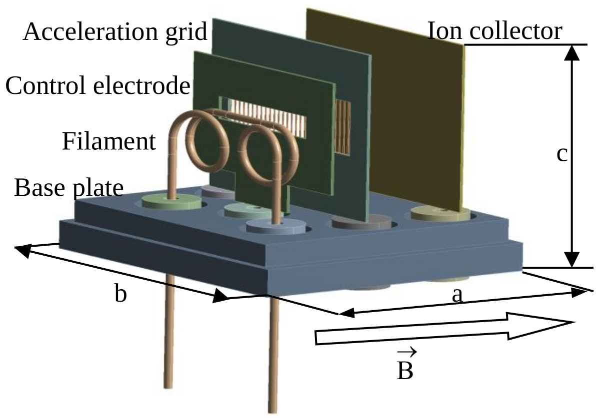

Fig. 1. Pressure gauge main parts assembly

The orientation, marked in Fig. 1 by $\vec{B}$ within the magnetic field is important for the proper functionality of the PG [2]. The assembly consists of a filament made of tungsten or tungsten alloy and control electrode, accelerator grid, ion collector made of stainless steel. All parts are ceramics insulated and fixed by brazing in the base plate made of stainless steel. The outer outline of the so called head is a*b*c ≈ 20*20*20 mm. Among all other equipment parts only the filament part will be the main subject of analyses in this paper. Beside of the filament shape shown in Fig. 1, called "spirally", the

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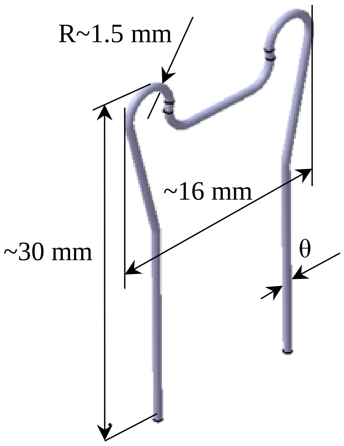

Fig. 2. Filament shape called "planar"

shape called "planar" (Fig. 2) has been considered as well. Since the filament wire diameter (θ) for DC driven heating is typically 0.6 mm, for AC driven heating two wire diameters 0.2 mm and 0.4 mm have been considered.

3. Numerical simulation and discussion

The aim of the numerical analysis or structural optimisation of the filament heated by AC is to find out the frequency of the heater current for a proposed design until the stresses or displacements caused by alternating Lorentz-forces (jxB) become acceptable (i.e. are below material limits). The applied procedure of the filament structural optimisation by numerical simulation is shown in Fig.3. The analyses begin with a transient thermal followed by an electromagnetic and finally a structural dynamic analysis. The above listed procedures have to be repeated in a do loop to improve the design and/or boundary conditions (BC) until the optimisation conditions (stresses or displacements) are satisfied. The designation above the boxes are the single analysis input parameters and the entities below are the analyses outputs.

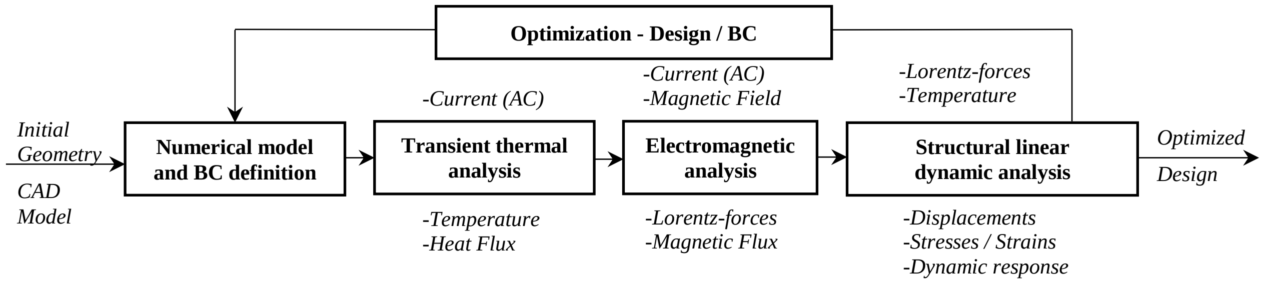

Fig. 3. Flow diagram of the filament Multiphysics numerical structural analysis

Two finite element (FE) models with different filament shapes have been prepared as follows:

- Filament shape = "spirally" and "planar"
- Filament wire diameter = 0.2 and 0.4 mm
- AC amplitude (I_0) = 2.0, 4.0 and 6.0 A
- AC frequency = 1 – 50 kHz
- Target temperature = ~1800 K ($\pm$ 100 K)

In theory the current is defined by the filament diameter for a certain material and the target

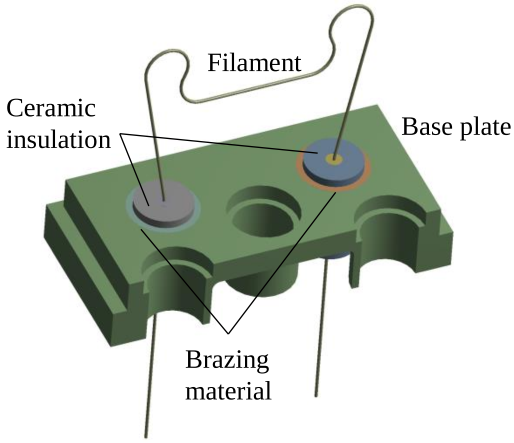

Fig. 4. FE model with "planar" filament

temperature. That is the reason why we use the approximately sign for the target temperature. Moreover, the filament operating temperature is not a fix value, it depends on work function and thus is not constant. For the choice of the AC frequency range the parameters of commercial equipment were considered. Fig. 4 shows the FE model with exemplarily "planar" filament and different material mixture. With the aim to avoid possible inaccurate results for filament stresses the manufacturing process (brazing) should be taken into account by the numerical simulations.

Pure tungsten material properties [3] have been used in present analysis. The FE model main features like filament material properties, electrical resistivity, thermal conductance and radiosity are defined entirely as temperature dependant. For these analyses the commercial numerical analysis package ANSYS [4] including the MAXWELL extension have been used.

Fig. 5 shows the result plot of the transient thermal analysis of the "spirally" filament. This analysis has been performed for a filament made of tungsten with a wire diameter of 0.2 mm and heated by AC current with an amplitude of 2.0 A. Main boundary conditions are the bulk temperature defined as 300 K and the base plate temperature defined as 600 K. The AC frequency does not play any role for filament heating since the AC frequency range does not induce any skin effect in the present wire cross-section. Additionally, the parametric transient temperature analysis provides the optimal effective filament length at approximately 60 mm. The effective filament length (hot part) is the part above the base plate between both fixations. Accordingly, the maximal temperature does not rise if the effective filament length increases.

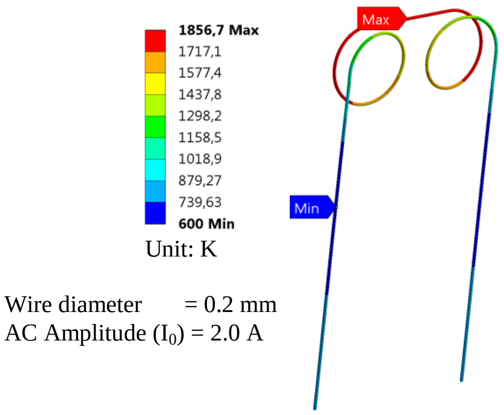

Fig. 5. Filament temperature ("spirally")

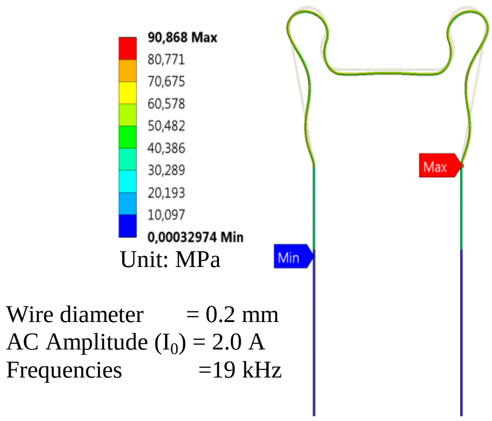

Fig. 6. Filament stress ("planar")

Moreover, this analysis shows that the variation of the base plate temperature has hardly any influence on the maximum filament temperature.

The subsequent electromagnetic analysis is not described here in detail. The Lorentz-forces needed in structural linear dynamic analysis have been calculated for both FE models with BC for current values of 2.0 A, 4.0 A and 6.0 A, and with a homogeneous background magnetic field of 8.0 T.

The structural linear dynamic analysis has been performed with the Lorentz-forces from electromagnetic analysis performed by the magnetostatic method. Actually, the harmonic response analysis has been used to determine the response of the structure to loads that vary sinusoidal (harmonic) with the time, according to:

$$F(t) = F_0 \sin(\omega t) \qquad (2)$$

where F_0 [N] is the force amplitude, ω [Hz] is the angular frequency and t [s] is the time. This is a linear analysis, therefore non-linarities such as plasticity are not considered here.

The harmonic method has been used exemplarily for the analyses with frequencies ranging from 1.0 kHz to 50.0 kHz with a step of 1.0 kHz. This procedure has been chosen for the quick search of the load frequency which provides the lowest stresses for a predefined filament design. For a more refined frequency choice, final analyses should be performed beginning with magneto-dynamic analysis. Since, present analyses have been performed at room temperature the operating temperature in the final analysis has to be considered as well. This step is not a subject of the present paper.

Fig. 6 exemplifies the stresses at a filament deformed (multiply increased) structure for load frequencies of 19.0 kHz. The maximal stresses occur mostly at the region of fixation. Consequently, the transition area between the filament and the insulation has to be designed as smooth as possible. The design and the fixation play, besides the load frequencies, a key role for the stress or deflection magnitude at the filament. Fig. 7 shows exemplarily the maximal Mises peak stress over the frequency range. In this plot areas with the lowest stresses are distinctly identifiable. These frequencies provide at the same time the lowest deflections and thus are suitable to be chosen for filament operating conditions. Especially, the relative large frequency regions with nearly equal low stresses are convenient for the filaments stable operation.

Table I shows a summary of the results for both models. This table reveals the diversity of variables applicable for filament structural optimisation. While the filament type "spirally" with the diameter of 0.4 mm and for both currents, according to the stress level, seems not to be feasible, the filament type "planar" seems to be basically feasible. The lowest stress, especially important for filament life cycle estimation, has been found in case of the "spirally" design for a wire diameter of 0.2 mm and current amplitude of 2.0 A with a magnitude of 70.0 MPa. For the "planar" design the lowest stresses were founded for diameter of 0.4 mm and the current amplitude of 4.0 A with magnitude of 77.0 MPa. Although the "planar" design has been preferred in respect of the "spirally" type because of simpler design and risk of short circuits caused by filament deformations in operation, the "spirally" type provides lowest stresses what is the most important optimization parameter in present analysis.

Particular attention should be paid to the choice of the filament operating region with respect to the changing heating current depending on work function, which causes change of frequencies and thus the change of stresses and displacement magnitudes.

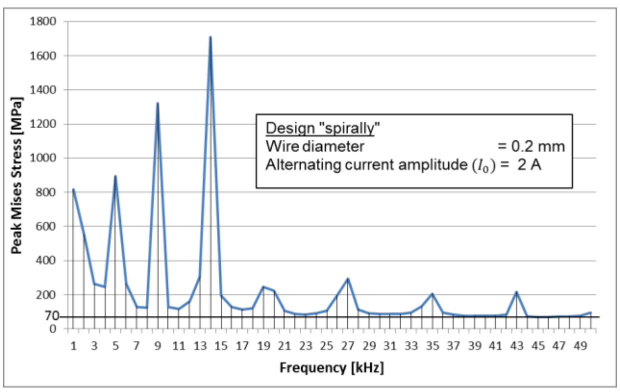

Fig. 7. Mises peak stress versa frequencies ("spirally")

Table I. Results summarisation

	Filament type "spirally"					Filament type "planar"				
	Diameter 0.2 mm			Diameter 0.4 mm		Diameter 0.2 mm			Diameter 0.4 mm	
Alternating Current (I_0) [A]	2	4	6	4	6	2	4	6	4	6
Frequency Range [kHz]	37-41 (42-49)	37-41 (42-49)	39-41 (44-48)	11-25 (27-49)	11-25 (27-49)	18-20 (43-47)	43-47 (35)	36 (43-46)	20-30	20-30
Min. Operating Mises Str. [MPa]	70	78	88	150	200	90	94	108	75	80
Deflection [mm10^{-3}]	1.8	2.2	2.8	4.5	5.5	4.1 (1.5)	1.92 (2.2)	3.5 (2.3)	1.2	1.33

Regarding to the filament operating conditions, primarily the very high operating temperature (1800 K) in combination with dynamic loading, the pure stress analysis only will not be sufficient for the assessment of the filament design or structure integrity.

The fatigue analyses, with respect to dynamic loads, and the creep analysis, with respect to high operating temperature, have to be performed as well. Since the load frequencies are very high, the classical fatigue analysis which provides the life cycle assessment until 10^8 cycles does not make much sense in the present case. The fatigue analysis has to be performed according to operating conditions for load cycles $>10^8$, called very high cycle fatigue (endurance).

However, the higher operating temperature stimulates the creep process which is additionally accelerated by cyclic loadings. Also, at the critical regions of structural part, two processes the fatigue and creep, which independently from each-other lead to the same aim, act to the structural part failure. Thereby, the source of mechanical or thermal cyclic loadings does not play an important role. In both cases the base for the life cycle estimation makes the rule of linear damage accumulation caused by different mechanisms (known as Palmgren-Miner hypothesis), as follows:

$$D_f = D + D_{cr} = \frac{n}{N} + \frac{t}{t_{cr}} \qquad (3)$$

where D_f is the total damage of structural part at the date of failure, $D_f \approx 1$, D is the damage of structural part caused by fatigue, D_{cr} is the damage of structural part caused by cyclic creep, n is the total number of load cycles, N is the cycles number until failure, $t = n / f$ [h] is the total creep time, f [h^{-1}] is the cycles number at unit time (t) and t_{cr} [h] is the time until the quasi static failure caused by creep at the amplitude level of the cycle`s.

While thorium oxide doped wolfram (e.g. $W-1ThO_2$) is used with respect to work function the tungsten with rhenium (e.g. $W-3.6\mathrm{Re}-1ThO_2$) as supplement is recommended by many authors [5] with respect to material dynamic properties.

4. Conclusions

This paper presents a numerical feasibility study of a hot cathode ionisation gauge used for neutral gas density measurement heated by alternating current. Integrated multiphysics numerical analyses are presented. The analysis begins with thermomechanical followed by electrodynamic and finally structural dynamic analysis. Exemplarily, two different filament designs with different wire diameters and different heating power have been evaluated. The lowest stress, especially important for filament life cycle estimation, has been found in case of the "spirally" design for a wire diameter of 0.2 mm and current amplitude of 2.0 A with a magnitude of 70.0 MPa. For the "planar" design the lowest stresses were founded for diameter of 0.4 mm and the current amplitude of 4.0 A with magnitude of 77.0 MPa. Moreover, the important issues for developing such a filament conceptual design like fatigue and creep of the filament are discussed as well. Finally, for a more precise numerical evaluation of a proposed filament design the material properties have to be known, which should be usually determined by tests.

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References

[1] J. M. Lafferty, Book ISBN 0-471-17593-5, 1998 John Wily & Sons, Inc.

[2] G. Haas and H.-S. Bosch, Vacuum **51**, 39–46 (1998), http://dx.doi.org/10.1016/S0042-207X(98)00131-6

[3] ITER Material Properties Handbook, ITER Document No. G 74 MA 9 00-11-10 W 0.1 (2001)

[4] ANSYS, Inc. Products Release 17.0 (2016)

[5] A. Luo et al., High temperature tensile properties of W-Re-ThO2 alloys, Mat. Sc. and Eng., A148, pp. 219-229, 1991.