Physical basis of the device for surface cleanliness measurement

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Abstract. The physical model of the device for surface cleanliness measurement and its technical realization are being considered in this paper. The number of gas monolayers being sorbed on the experimental surfaces is considered as a cleanliness parameter of these surfaces. The calibration graphs for the device under variable conditions of gases residual pressure, temperature and relative humidity are shown.

1. Actuality of cleanliness measurement

The problem of surface cleanliness measurement in nuclear and space technologies that is calculated as a number of sorbed gases monolayers is in the absence of sensors or even methods known by nowadays that could provide it direct quantitative estimation. Nevertheless the authors have realized it through some indirect and labour-intensive methods.

Scientific and social importance of the surface cleanliness sensor that is under development best of all may be illustrated with IVC-20 Secretariat decision [1] and e-mail letter from Prof. Jay Hendricks to Prof. Deulin (Chair VSTD IUVSTA): “We are working both with accelerators/R&D and industries. As result of our work we started to define purity classes. First purity classes are fixed for UCV (ultra clean vacuum similar to UCV purity classes we are working on purity classes for UHV/XHV”.

2. Theoretical foundation of the sensor working

The first theoretical estimation of coverage Θ parameter in region of high vacuum we call [4] Henry equation:

Θ = K_G P ,

(1)

where K_G – Henry gas constant; P – residual pressure.

The more complex equation for theoretical coverage Θ parameter estimation in high and middle vacuum we call Langmuir [8] equation:

u = \frac{bP}{1+bP} ,

(2)

where b – gas constant; P – residual pressure.

The most complex equation for theoretical coverage parameter Θ estimation in wide vacuum region, close to atmosphere, we call BET (Brunnauer Emmet Teller) equation [11], where P – residual pressure over the surface; P_L – sorbed gas saturation pressure; E_a – sorption heat; E_v – evaporation (condensation) heat of gas being sorbed; R – gas constant; T – surface (gas) temperature:
The next equation was done [3] for coverage parameter $\Theta$ estimation in process of surfaces contacting in vacuum mechanisms:

$$\Theta \leq \frac{P d \alpha}{4 \sqrt{2 \pi k T}} \left[ \frac{L}{V} - \tau_0 \exp\left(\frac{E_d}{RT}\right) \right],$$

(4)

where $T_a$ – mean temperature of contacting surfaces after contact, K; $L$ – mean distance between micro roughness on contacting surfaces, m; $V$ – friction speed, m/s; $\alpha$ – sticking coefficient; $k$ – Boltzmann constant; $\tau_0$ – adhesion constant, s; $d_0$ – gas molecule diameter $d_0 \approx 3 \cdot 10^{-10}$ m; $m$ – sorbed molecule mass, kg.

Well known physics position says that energy (force) of links between sorbed molecule and a surface depends on “molecule–surface” distance and may be described with Lennard-Jones equation [8]. That equation shows that the largest energy (force) exists in a zone of first monolayer where “molecule–surface” distance is equal to sorbed molecule diameter $d_0 \approx 3 \cdot 10^{-10}$ m (zone of “chemistry sorption”):

$$E(X) = 4\varepsilon \left[ \left( \frac{r_0}{r} \right)^{12} - \left( \frac{r_0}{r} \right)^{6} \right],$$

(5)

where $\varepsilon$ – potential linking energy; $r$ – distance between centers of molecules; $r_0$ – distance where the energy takes zero value.

Figure 1 shows an equation (5) graphical interpretation where distance $r$ (marked with symbol $X$) increasing leads to sorption energy variation till minimal values that we call “chemical” and “physical” sorption energy.

Taking into account that mentioned energy influences on friction force, we can use this effect for coverage $\Theta$ value detection. In figure 1 “sorbed molecule–surface” linking energy $E(X)$ takes negative values, but in engineering practice the friction force $F_T$ as a function of $E(X)$ cannot be negative.

To eliminate this contradiction let’s represent diagram from figure 1 in inverted form (figure 2(a)) with a friction force $F_T$ as a function of distance $X$. The “inverted” diagram from figure 2(a) comparison with engineering experimental results in figure 2(b) shows their identity.

![Figure 1. Lennard-Jones diagram of the sorption energy as a function of “sorbed molecule–surface” distance.](image)

We can see mentioned “negative” energy from figure 1 can be presented as a positive friction force $F_T$ and may be used for the sensor calibration. The results of static friction force coefficient measurement may be presented (figure 2(b)) as a function of distance $X$ (“sorbed molecule–surface”) or a function of coverage $\Theta$ value after recalculation [2]. Taking into account the physical sense of Lennard-Jones diagram we understand that $F_T$ parameter value that is equal to “zero” in figure 1 and figure 2(a) was obtained theoretically and couldn’t be measured that is reflected in graph (figure 2(b)).
Figure 2. Lennard-Jones diagram presentation: into “engineering” inverted form (a); into friction force $F_T$ as a function of distance $X$ (coverage $\Theta$ value) (b).

3. Sensor design description

The cleanliness sensor patented principle [5] may be realized in different design variants. The presented in figure 3 design is based on three polished plates usage, one of which is movable (5) and is clamped between two another ones (4, 6). Piezo drive 1 presses plate 4 to a plate 5 with the normal force $F_N$. Piezo drive 10 provides the tangential force $F_T$ by moving plate 5 with element 7. Sensors 5 and 9 being fixed on elastic elements are used for normal force $F_N$ and tangential force $F_T$ measurement respectively. Base 11 with a frame 2 are fixed on UHV (Ultra High Vacuum) flange CF40.

The design idea shown in figure 3 was realized in prototype that may be seen in figure 4. The sample of cleanliness sensor model was fixed on UHV flange Conflat CF40. Electric feedthrough fixed on CF40 UHV flange provides the signal transmission between control units that are in atmosphere and piezoelectric drives with strain gauges that are in vacuum.

Figure 3. Design scheme of the surface cleanliness sensor: 1 – piezoelectric drive for the force $F_N$ creation; 2 – piezoelectric drive for the tangential force $F_T$ creation; 3 – frame; 4 – elastic elements; 5 – sensor for the normal force $F_N$ measurement; 6 – sensor for the tangential force $F_T$ measurement; 7 – plate holders; 8 – clamping plate; 9 – movable plate; 10 – static plate; 11 – base, 12 – UHV flange CF40; 13 – UHV electric feedthrough.

Figure 4. The surface cleanliness sensor specimen on UHV flange CF40.
The sensor novelty is that it makes possible to measure the coverage coefficient $\Theta$ directly on plates 8–10 (figure 3). The “Control unit” (figure 3) receives analog signals from $F_N$ and $F_T$ measuring strain gauges, converts them to digital format and transmits to the personal computer COM port. The PC program collects the data from control unit in form of a static friction force coefficient:

$$\mu_s = \frac{F_T}{F_N}. \quad (6)$$

Finally the program processes the accumulated data of static friction force $\mu_s$ coefficient values using calibrating diagrams and presents the result of measurement in form of a key parameter – coverage $\Theta$ coefficient.

4. Experimental base
The method of the cleanliness parameter measurement was patented in 2005–2008 [4, 5]. The experimental data based on used methods [3] show the ways for the sensor realization, as we can see in figures 2, 5.

![Figure 5](image)

**Figure 5.** Experimental data of static friction coefficient as a function of: pressure [1] (a), temperature [6] (b), relative humidity [2] (c).

The experimental data of static friction coefficient measurement at variable parameters $P$, $T$, $RH$ (figure 5) shows the influence of these parameters on the coverage $\Theta$ parameter and may be used for the cleanliness sensor calibration. Thus measuring the static friction force coefficient with our sensor we can transform its values into coverage $\Theta$ parameter [2, 10] that would describe the number of sorbed gases monolayers on the surface in specific conditions of pressure, temperature and relative humidity of the sensor ambient. Also we must remember that we consider this $\Theta$ parameter as a cleanliness factor.

5. Summary
The physical base of device for the surface cleanliness measurement was done and used in practice. The sensor design main idea to consider “cleanliness” of the object surface as a number of sorbed gas monolayers is being realized and show its productivity. Theory shows that all the experimental results at residual pressure, temperature, humidity and materials variation may be presented as a function of coverage coefficient that may be used for cleanliness estimation by the sensor being designed in BMSTU, Russia. The sensor calibration graphs show the sensor marketability for using it in conditions...
of residual pressure, temperature, relative humidity variation, i.e. in the conditions being demanded for nuclear, vacuum and space technology.

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References
[1] Deulin E A, Gatsenko A A and Loginov B A 1999 Surface Science 433-435 288–92
[2] Deulin E A, Mikhailov V P, Panfilov Yu V and Nevshupa R A 2010 Mechanics and Physics of Precise Vacuum Mechanisms. Fluid Mechanics and Its Applications 91 (Springer)
[3] Deulin E A 2010 Trenie i smazka v mashinakh i mekhanizakh 9-10 35–43, 43–7
[4] Deulin E A 2005 Friction vacuum gauge. Patent RU 2263886
[5] Deulin E A 2008 Method of measuring vacuum. Patent RU 2316744
[6] Gladyshev I V 2002 Proceedings Nordtrib, Keynotes and Abstracts p 176
[7] IVC-20 Secretariat – People-X Inc.: contact@ivc20.com
[8] Langmuir I 1913 Phys. Rev. 1 337
[9] Lennard-Jones J E 1924 Proc. Roy. Soc. A106 463
[10] Rozanov L N 1990 Vakuumnaya tekhnika (Moscow: Vysshaya shkola)
[11] Dushman S 1962 Scientific Foundations of Vacuum Technique (New York-London: John Wiley & Sons)