APPLICATION OF IR-RADIOMETRIC DIAGNOSTICS FOR CONTROL OF VACUUM CONNECTIONS OF ELECTROPHYSICAL INSTALLATIONS

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The methods of IR-radiometric diagnostics of vacuum systems have been worked out. Several mechanisms are proposed that change the temperature field in the defect region. Depending on the type of defect, the main types of temperature anomalies are identified. The influence on the results of thermo graphic survey of such parameters as the assembly quality of the accelerator assemblies, the state of the material, and the cleanliness of the flange surface was studied. The possibility of detecting suction in case of a breach of air tightness of ducts is shown. To detect micro leakage of vacuum connections of the accelerator flanges, an IR-radiometric control is performed. Found leaks based on the received thermograms. They are found in the region of gas throttling or areas of variation in of the coefficient of radiation. Systematization of thermo images of defects in vacuum systems has been carried out. Systematized on the basis on the types of damage.

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INTRODUCTION

Enormous attention is given the questions of serviceability of vacuum equipment. Deterioration of efficiency of vacuum systems reduces efficiency of work, promotes losses. Probability of appearance of emergency situations is also high. This entails the appearance of significant capital expenditures. At the decision of task of increasing the efficiency of equipment, important is control of its condition. With the help of technical condition monitoring, the problem of timely detection of defects is solved. Defects can have different types. The criticality of the revealed violations is determined. Control of development of defects is conducted. For the removal of defects, work is performed. All of it to a full degree belongs and to work of equipment intended for conducting of physical experiments. The main indicator of good condition of vacuum systems is absence of points of leakage. The questions of finding of leak are studied for a very long time. A problem remains actual and presently. Questions are expounded in bibliographies to works [1, 2]. When conducting physical experiments, a considerable amount of time is spent on preparing the equipment for the experiment. The list of works includes the procedure for assembling the equipment. Such measures increased efficiency of work of equipment: reduction of time of search of violations of vacuum, quality of adjoining of details.

PURPOSE OF WORK

Diagnostics of efficiency of assembling of vacuum connections. Development of methods of IR-radiometric control of power equipment.

THE MAIN PART

For implementation of these works, on the basis of methods of IR-radiometry, it was suggested to apply a infrared thermal imaging technique. Principles of work of thermovision technique are based on registration of stream of infrared from the surface of object. The got information is designed as thermograms, graphs, charts, tables. The analysis of results allows to define the change of the temperature field on the surface of the object of investigation. A brightness and colour saturation of image on thermograms represents relief of temperature. Distributing of temperatures on the surface of the object allows to find out latent defects. The question of the correspondence of a certain defect to a given thermal trace is a difficult task. It is necessary to consider the thermal, mechanical processes that occur in the object of investigation. In interpreting the results obtained of took into account such factors: different features of configuration, structure of equipment, conditions, and the influence of external factors. This work is very laborious and not always gives a unambiguous result. Therefore, for the practical use of thermography methods, there is a necessity to create a database of the results obtained.

Infrared radiation from the surface of object, which is fixed by a thermal imager it can be described through the law of Stefan-Boltzmann:

$$W_\lambda = \varepsilon \cdot \sigma \cdot T_\Phi^4 \cdot \cos\alpha, \tag{1}$$

where ε – is the coefficient of surface radiation; $\sigma = 5.67 \cdot 10^{-8}$ W/(m^2·K^4) – is the Stefan-Boltzmann constant; T_Φ – is the actual temperature at the surface of the object in degrees Kelvin; α – is the viewing angle (the angle between the thermal imager and the normal to the plane of the object under study).

Performing simple mathematical transformations, we obtain the dependence of the actual temperature on the radiation temperature:

$$T_\Phi \approx \frac{T_{Рад}}{\sqrt[4]{\varepsilon}}. \tag{2}$$

Consequently, the measured radiation temperature has direct dependence on an actual temperature and from the coefficient of radiation. An account of parameter of ε is substantial at implementation of IR-radiometry. He reflects the differences of radiate capabilities of different surfaces. I.e. the polished surfaces ($\varepsilon \leq 0.3$) on thermograms have a display more cold, than areas are black ($\varepsilon \geq 0.85$). A basic error in researches is brought in by the coefficient of radiation. On the basis of analysis of changes of the temperature field on the surface of the equipment, it is possible to conclude about the state of vacuum connections and vacuum equipment.

A substantiation of the possibility of IR-radiometric diagnostics of vacuum equipment is given in works [3–5]. The technique of studying vacuum equipment using IR-radiometric diagnostics consists of several tasks. Their solution is performed depending on the complexity of the equipment, the level of vacuum. The most effective IR-diagnostics are in screening mode. Those operative finding of violations. At the same time, the main requirement for IR-radiometric diagnostics is obtaining a quality picture. In future, on the basis of the resulting thermogram, we draw conclusions about the vacuum system.

RESEARCH DISCUSSION OF THE RESULTS

PERFORMING RESEARCH FOR MACRODEFECTS OF VACUUM SYSTEMS

Practical tests were carried out. The evaluation of the effectiveness of the methods of IR-radiometric diagnostics was performed. IR-radiometric researches of air ducts of the systems of ventilation of the physical settings were conducted in our case. The results of the studies are shown in Figs. 1, 2.

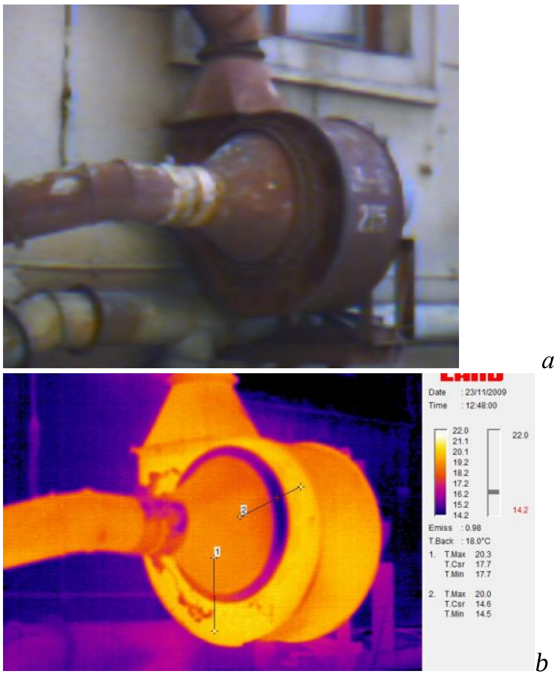

Fig. 1. Results of IR-radiometric control of the of the system of ventilators: a – is a visible image; b – is a IR-thermogram

Of Fig. 1,a we get that the research of equipment in the visible range does not yield results. When studying the thermogram (see Fig. 1,b), a decrease in the temperatures in the area of the gasket between the parts of the was observed.

It can testify to the presence of suction of air in this area. Additional information is given by the study of charts of graphs of the temperature field.

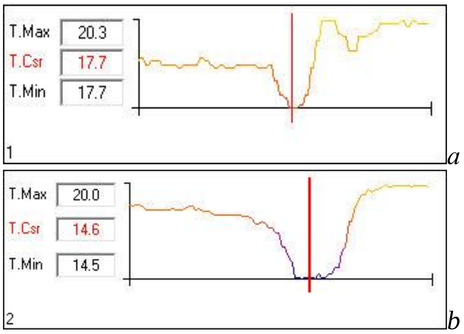

Fig. 2. Graphs of temperature changes along the cross-section: a – cross-section 1; b – cross-section 2

Fig. 2,a shows the temperature change along cross-section 1. On the thermogram, we observe a change the light background in the area of the gasket. There is small violation of integrity of gasket in this area. Small suction of external air is present. Thus there is cooling of area of suction. In area of cross-section 2 look after the considerable change of colour gamut. It testifies to more considerable violation of gaskets. In this area, there is a more significant suction of external air. This is evidenced by a stronger cooling of the gasket area. Comparing the temperature curves of Fig. 2, we see that in the area of the second cross-section the temperature falling is more significant. So on the first cross-section a temperature changed on 2.8 °C, and in area of the second cross-section on 5.5 °C. Thus, in the case of strong air currents, it is possible to detect suction, insulation faults with high efficiency.

PERFORMING RESEARCH FOR MICRODEFECTS

In the case of appearance of microdefects a situation with their determination substantially becomes complicated. This is notedly, when examining physical installations. For their verification, it is necessary to consider the main factors that can influence the temperatures change in the defects area.

Defect – any leaks in vacuum systems. When studying temperature gradients, it should be taken into account that the appearance of a leak is accompanied by microflows of gases. Several factors influence the temperature change in the defect area.

Basic it is been: a – cooling of the walls of the leak channel due to the flow of gas; b – cooling of the gas outlet area or gas suction due to its expansion (throttling effect); c – is a change of coefficient of radiation in area of defect. We will conduct the estimation of influence of all these effects on the change of temperature. Cooling of the walls of the channel during the flow of gas through it occurs due to the motion of gas flows. In the case of flowing of more heated gases, as compared to the walls of channel, there is their heating. However, the heating is insignificant. Using the equation of Bernoulli, we can estimate the value of the energy which is selected at motion of gas stream.

The throttling effect can be calculated on the basis of the Clapeyron-Mendeleyev equation:

$$\frac{P_i V_i}{T_i} = \frac{P_k V_k}{T_k}, \tag{3}$$

where $P_{i,k}$ – pressure inside and outside the volume; $V_{i,k}$ – volume inside and outside; $T_{i,k}$ – temperatures on the inside and on the surface. Having carried out the calculations, we find that when the vacuum is in the order of 10^{-5} mm of mercury and the external pressure in the atmosphere, the temperature changes are 0.03…0.2 °C.

Modern thermal imaging equipment is able to record these temperature changes. Physical installations are made of metals. However, considering that metals have high heat transfer coefficients (for steel 15…30 W/(m·K)), the temperature change in the area of leakage will be significantly lower than the permission of thermal imaging technology.

In the case of manufacturing a accelerator flange of plexiglas or the presence of coatings (ceramics, plastic) on the surface of the metal flange, it is possible to detect leaks.

To test the efficiency of our methods, studies were carried out on a real physical installation (accelerator).

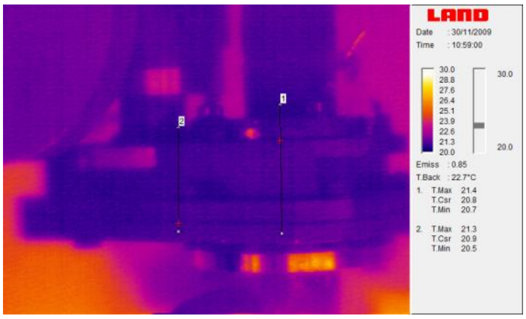

Fig. 3. The thermogram of the accelerator flange without defects

Work was done on IR-radiometric inspection of the accelerator flanges. Fig. 3 shows the thermogram of the flange, which has no defects, and there are no leaks. This is also evidenced by the graphs of temperature changes along cross-sections 1 and 2 (Fig. 4).

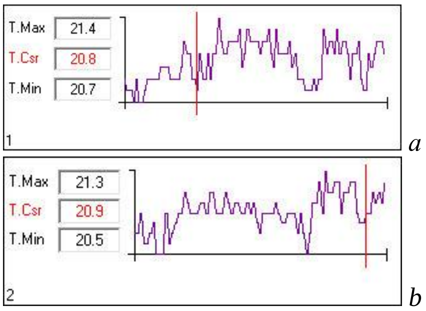

Fig. 4. Graphs of temperature changes along the sections of the accelerator flange (without defects): a – is a cross-section 1; b – is a cross-section 2

Analysis of the graphs shows that the temperature on the surface of the flange varies insignificantly. There are fluctuations near the middle temperature. These fluctuations depend on temperature fluctuations. The temperature changes on the individual elements of the thermal imager array.

The red vertical bars mark the points of the gaskets. On them also there are not out-riggers of the temperature field. The thermal imaging data is confirmed by the practical results of this block. Hes works in a constant mode. He keeps vacuum.

For comparison, a study of a similar accelerator flange was performed, during exploitation of which there were problems. Its thermogram and the visible image are given in Fig. 5.

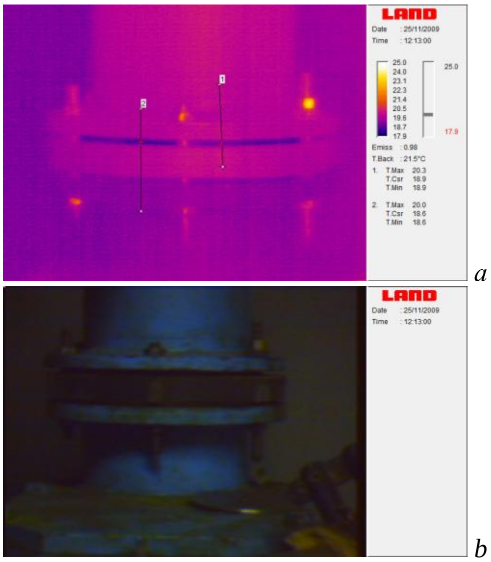

Fig. 5. The thermogram (a) and the visible image (b) of the accelerator flange with violations in the area of the upper gasket

In the area of the upper gasket, a temperature anomaly is observed. In the visible image of Fig. 5,b, the anomaly is not fixed. Studying its change allows us to make an assumption about the violation of the density of the upper gasket between the individual elements of accelerator flange. For a more detailed analysis, consider the temperature graphs in Fig. 6.

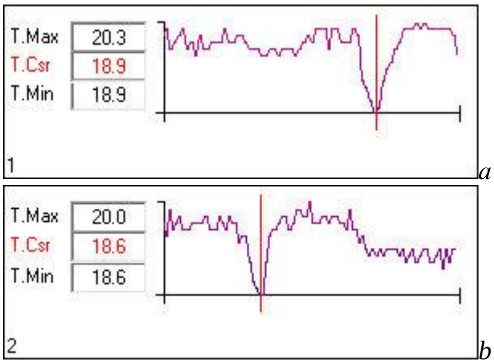

Fig. 6. Graphs of temperature changes along sections of the accelerator flange (defect in the area of the gasket): a – is a section 1; b – is a cross-section 2

Two graphs of temperature variation along cross-sections 1 and 2 were obtained. Cross-section 1 passes through the upper part of the flange, the area of the body of the upper accelerator flange, the upper gasket, the body of the adapter. An abnormal temperature change of 1.4 °C is observed only in the area of the gasket. Cross-section 2 was so placed that it captured a larger space: the upper flange, the upper gasket, the adapter, the lower gasket, the lower flange. The temperature jump (1.4 °C) is observed only on the upper gasket.

Measurements were made using a halogen leak detector. Found an insignificant leak in this area. At additional inspection have found out non-uniform clamping of a lining. Bolts were tightened. The leak was eliminated. As follows from the calculations, it is impossible to detect a leak on the basis of the outflow of gases (the Bernoulli law and the Clapeyron-Mendeleyev law work). However, a leak was detected. Therefore, in this case another mechanism works. The change in the temperature field depends on the change of coefficient change of the temperature field is a change of coefficient of radiation.

The appearance of different coefficients of radiation in neighboring areas is associated with many causes. In our case – the unevenness of the tightening is either gasket or flange. This changes the structure of the surface layer, and hence the radiation coefficient also changes.

Radiation temperature is influenced by the coefficient of radiation [6, 7]. Thus, even with minor defects, them it is possible to detect (by changing the coefficient of radiation).

The vacuum equipment was checked in the case of under constraint. Thus, the quality of the connection of the flange at an increased internal pressure was considered. The image in the optical range and the thermogram are shown in Fig. 7. During the examination of this node in the optical range, no violations were detected. A more accurate examination was performed using IR-radiometry. In this area, a spot that was different in color and intensity was detected.

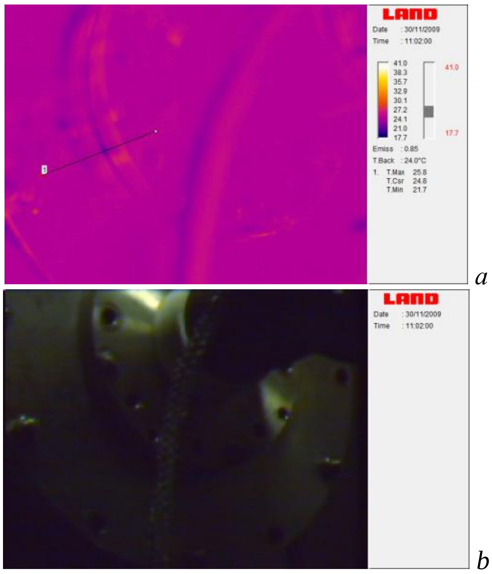

Fig. 7. The area of the accelerator flange, where a gas leak is detected: a – is a thermogram; b – is a visual image

The cause of the appearance of a temperature anomaly is a defect. The nature of the defect was based on the uneven fixation of the fixing screw-nuts. In addition, we studied the graph of temperature changes in this region (Fig. 8).

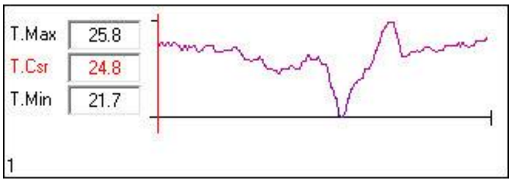

Fig. 8. Graph of temperature changes along the cross-section of the accelerator flange

In the temperature anomaly area, we have a temperature down of 3.1 °C. The temperature peak is narrow, what indicates the localization of the defect. In the area of the anomaly, was no fixing screw-nut (see Fig. 7,b) therefore the flange was not fully depressed.

Placing the missing bolt and its tightening made it possible to liquidate the leak. Further examination of the accelerator made it possible to reveal another region with an anomalous change in the temperature field (Fig. 9).

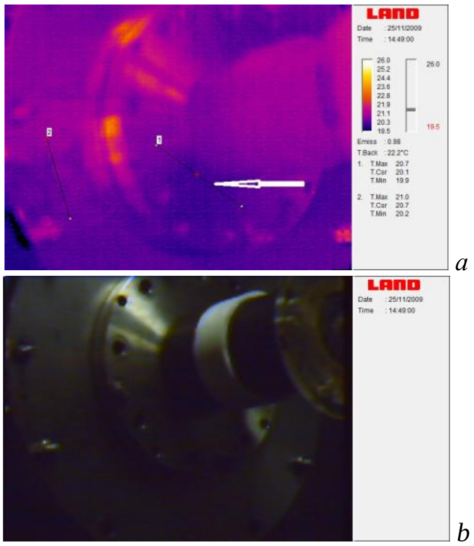

Fig. 9. The flange area where a gas leak is detected (the effect of throttling): a – is a thermogram; b – is a visual image

From previous it was different in that it was noticeable effect of throttling. On the thermogram (see Fig. 9,a) the white arrow marks the area where a spot with a different color is located. A darker color indicates a lower temperature. To test the hypotheses of reflection or shading, an analysis of the temperature variation charts was carried out. Cross-sections, according to which temperatures were measured, passed through different surfaces. From Fig. 9,b it was determined that in the region of cross-section 1 there is a shadow from the illumination. There were no more features in this area.

The graph of temperature changes along this cross-section is shown in Fig. 10,b. We observe a slow change in temperature. Jumps only on separate elements of the receiving matrix. The maximum temperature is 21 °C, the minimum is 20.2 °C.

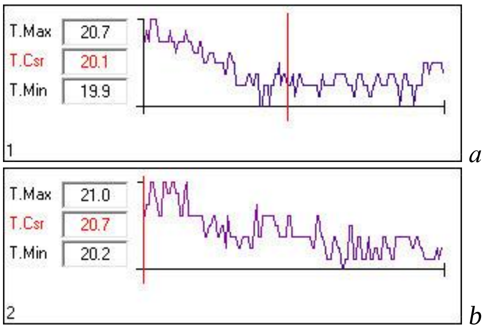

Fig. 10. Graphs of temperature changes along the cross-section of the accelerator flange (the effect of throttling): a – cross-section 1; b – cross-section 2

And it is a minimum temperature on all shaded surface. Cross-section 2, marked by a white arrow, passes through the area where a defect is suspected. The minimum temperature is 19.9 °C. It below than all minimum temperatures on the surface. The recession of the temperature field is smooth. With a high probability there is a defect in this area. In our case – leak. Thermal trace is formed due to the throttling of gases. A cloud of more cold gas is above the surface of flange. This case is realized at the sevenfold difference of pressure. Thus, finding of leaks through IR-radiometric diagnostics, possibly in the case of wide difference of pressures into a volume and outside

CONCLUSIONS

1. The paper shows the possibility of using IR-radiometric diagnostics for examining vacuum systems of physical installations.
2. The basic mechanisms that are responsible for the change the temperature field in the region of defects of vacuum systems are determined.
3. Defects which arose up as a result of different types of violations are found. Defects are got from the results of thermografhic researches.
4. The basic features of characteristic displays of defects are offered. Systematization of defects was executed. It is done on the basis of analysis of got thermograms and charts of change of temperatures.

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ПРИМЕНЕНИЕ ИК-РАДИОМЕТРИЧЕСКОЙ ДИАГНОСТИКИ ДЛЯ КОНТРОЛЯ ВАКУУМНЫХ СОЕДИНЕНИЙ ЭЛЕКТРОФИЗИЧЕСКИХ УСТАНОВОК

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Отработаны методики ИК-радиометрической диагностики вакуумных систем. Предложено несколько механизмов, в результате которых изменяется температурное поле в области дефекта. В зависимости от вида дефекта выделены основные проявления температурных аномалий. Изучено влияние на результаты термографической съемки таких параметров: качества сборки узлов ускорителя, состояния материала, чистоты поверхности фланцев. Показана возможность обнаружения подсосов в случае нарушения герметичности воздуховодов. Для обнаружения микротечей вакуумных соединений фланцев ускорителя выполнен ИК-радиометрический контроль. Были найдены течи на основании полученных термограмм. Они обнаружены в области дросселирования газов или областях изменения коэффициента излучения. Проведена систематизация термоизображений дефектов вакуумных систем на основе типов повреждений.

ЗАСТОСУВАННЯ ІК-РАДІОМЕТРИЧНОЇ ДІАГНОСТИКИ ДЛЯ КОНТРОЛЮ ВАКУУМНИХ З’ЄДНАННЬ ЕЛЕКТРОФІЗИЧНИХ УСТАНОВОК

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Відпрацьовано методики ІЧ-радіометричної діагностики вакуумних систем. Запропоновано декілька механізмів, за рахунок яких змінюється температурне поле в області дефекту. Залежно від виду дефекту виділені основні прояви температурних аномалій. Вивчено вплив на результати термографічної зйомки таких параметрів: якості збірки вузлів прискорювача, стану матеріалу, чистоти поверхні фланців. Показана можливість виявлення підсосів у разі порушення герметичності повітроводів. Для виявлення мікротечі вакуумних з'єднань фланців прискорювача виконаний ІЧ-радіометричний контроль. Були знайдені течі на підставі отриманих термограм. Вони виявлені в області дроселювання газів або областях зміни коефіцієнта випромінювання. Проведена систематизація термозображень дефектів вакуумних систем на основі типів ушкоджень.