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Safety assessment of the cooling water supply systems in the nuclear power plants using thermography monitoring

Thermography monitoring was applied to analyze the safety integrity of the cooling water supply systems in the nuclear power plants. The main purpose of this work was to assess the possibilities to improve the thermography monitoring techniques of the technical water supply control systems. It aims to study the peculiarities of the heat heterogeneities happened with latent leakage. Thermography data was examined using fractal segmentation methods which are considered to be perspective for further research.

Key words: *nuclear power plant, thermography, fractals, technical-water supply.*

Для оцінки надійності системи технічного водопостачання було застосовано метод термографічного моніторингу. Метою роботи було з'ясування можливості удосконалення технології термографічного моніторингу системи технічного водопостачання. Це здійснювалось шляхом аналізу особливостей температурних неоднорідностей, що могли бути спричинені схованими витоками. Термографічні дані аналізувались з застосуванням методів фрактальної сегментації. Показана їх перспективність для подальшого вивчення.

Ключові слова: *атомна електростанція, термографія, фрактали, система технічного водопостачання.*

Для оценки надежности системы технического водоснабжения был применен метод термографического мониторинга. Целью работы было установление возможности совершенствования технологи термографического мониторинга системы технического водоснабжения. Это осуществлялось путем анализа особенностей температурных неоднородностей, которые могли быть вызваны скрытыми утечками. Термографические данные анализировались с применением методов фрактальной сегментации. Показана их перспективность для дальнейшего изучения.

Ключевые слова: *атомная электростанция, термография, фракталы, система технического водоснабжения.*

Introduction

This work is an improved elaboration of the results and further advancements on the application of thermography monitoring of the cooling water supply systems in the nuclear power plants (NPPs) which were earlier presented in [1]. An increase of NPP safety requirements caused by the accident on "Fukushima-1" NPP, is expected to implement complementary state monitoring methods of equipment, communications and water reserves. Obviously, the variety of potential emergency and hazardous factors requires application of the comprehensive approaches for monitoring of the NPPs facilities. One of these methods is the thermal imaging. It is a classic non-destructive technique used for diagnostics of a wide spectrum of technological equipment, and it is actually applied for the safety integrity checks at NPPs [2]. This paper presents the results of the research, which goals were to study the possibility for improvement of the thermography control methods on the NPPs and to improve the corresponding data processing, particularly to monitor the cooling water supply systems and general environmental on-site conditions.

In this work we conducted fractal analysis to characterize thermograms. We tried to understand new opportunities of such potential data processing technique to increase the informational usefulness of thermograms. Fractal characteristics of thermograms are caused by two main factors, which correlate with the fundamental principles described in [3-9]. First, the physical object of research is characterized by fractal descriptors (incl. fractal dimension), therefore a phenomenon of thermal conductivity for certain object (e.g., crack or pit in a pipeline, corrosion damage of a valve, etc) may differ from the classical description. Second, existing noise in the thermograms has also fractal properties, thus, the actual signal may be potentially separated from noise to be treated independently. The concept of the fractal nature of thermographic data is still ambiguous, and requires a comprehensive exploration. Additionally, the data processing of the thermography data using filtering in terms of fractal descriptors may result in early detection and recognition of the heat heterogeneities, which can signal about the probable equipment failure.

It is also important to study a multifractal character of sequences of thermograms, because it may give important information about the dynamics of temperature field. Further, our preliminary attempts for processing the fractal character of thermograms are elaborated and discussed in a perspective for further implementation in the industry.

Materials and methods

We carried out measurements using thermal imagers Fluke Ti32, Land Ti814, which of both has the temperature detection matrix resolution of 320x240 pixels, an absolute accuracy of 0.05K. All thermographic imaging was performed with the cameras properly fixed on a stable holder.

Thermal field distributions of the soil surface, underground pipelines, pumping equipment, stop valves, facilities of spray ponds at NPPs were acquired (Fig. 1). Some measurements were carried out at night when temperature differences were bigger compared to the environment and the peculiarities of heat transfer were more visible. Our measurements included: the detection of thermal field anomalies, leakages, corrosion of coatings, possible damage (incl. crack propagation) of the equipment.

Except the classic thermography monitoring, the fractal nature of thermograms was studied in this research. The perspectives of the research in this field are explained here below. Fractals are geometrically complex objects, which are characterized by a property of self-similarity. The part of the fractal object resembles the whole object [5]. A fractal object is a set of points Υ in an Euclidean space, which has a fractional metric dimension D_M (according to the basic definition Minkowski and Hausdorff [3]) shown by Eq. (1).

$$\dim_M(\Upsilon) = D_M = -lim_{\eta\to 0}\frac{logN(\eta)}{log\ \eta}, \qquad (1)$$

where η – is a scalable step (aka kernel size), N is a minimal cover of a fractal object at η. On practice, an iteration procedure is used with changeable η through defining a ratio at different scales (2):

$$logN = A - B\ log\,\eta, \tag{2}$$

where A , B are constants defined from the proportions at diffent η assuming the proportion N-η to be linear. Therefore, the slope of the straight line is defined from a log-log dependence, further providing information about a scaling nature of an object, namely, the fractal dimension D_{frac}, which is proportional to B ($B = C - 2D_{frac}$, where C is the maximum dimension of the space in which the object is investigated). The fractal object can have a metric dimension higher that than a topological dimension. It should be noted that a term "fractality" is used in a simplified manner only for a statistical estimate of a fractal dimension, and other fractal descriptors are omitted in this research. Real images are always limited and have finite resolution, which greatly degenerates with a poor scalability. The strongest type of self-similarity of fractals is not correct, hence, we should deal only with the statistical self-similarity. The basic property of mathematically correct fractals – 'self-similarity' is neither possible to investigate nor apply in its full meaning for thermograms. It is necessary to highlight, that the final result is even affected by the nature of the observed object: its heterogeneity, texture, stationary, shape, position in space, the projection on the detector's surface. Therefore the relative simplicity of the grass cover as the object of research is essential to prove correctness of obtained results, for further application of fractal analysis for more complex objects. The variation of data sets ('temperature' or 'color') and its spatial distribution are the sources of fractality D_{frac}. It should be emphasized, that the magnitudes of the dimensions of statistically fractal objects are determined only approximately, and the estimates essentially depend on the applied numerical methods of calculation (e.g. box counting method, triangular prism method, Monte Carlo methods, etc). At the same time, one should not forget about the existing noise in the data sets, all sorts of distortion caused by the camera operator, and instrumental flaws.

In order to study the self-similarity of thermograms, the reduction of resolution was performed using arithmetic averaging to smaller dimensions. The arithmetic average $\overline{T_{kl}}$ and corresponding deviation d_{ij} were obtained according to the definitions Eq. (3) and (4). Deviations were calculated with respect to average values $\overline{T_{kl}}$ of frames (kernels) with size 2x2, 4x3, 8x6 (n x m, width x height):

$$\overline{T_{kl}} = \frac{1}{nm}\sum_{i,j}^{i+n,j+m} T_{i,j} \tag{3}$$

$$d_{ij} = \sqrt{\frac{1}{nm}\sum_{i,j}^{i+n,j+m}(T_{i,j} - \overline{T_{kl}})^2} \tag{4}$$

The final calculation procedure was the following: we partitioned and averaged thermograms accordingly to the frames sizes, determined the temperature mean values in every part of thermal image, and then estimated the deviations from corresponding mean for each pixel in the specified frame. After that, we generated grayscale and RGB images and used ImageJ software packages to build the fractal dimension field. The calculated fractal dimension field does not give just single value of D_{frac}, but it can have a wide spectrum of distribution of fractal dimensions of a thermogram. Thus, the fractal dimension field should be considered as a multifractal dimension distribution D_{MF}.

In this work we carried out the fractal dimension analysis of thermograms in terms of gray-level images (0-255 intensity), but all thermograms were presented in this article as RGB figures only for the sake of better visualization.

More specifically, the described approach was tested using the thermograms of soil surface, where underground utility lines are buried. A sequence of 3 thermograms of homogeneous natural ground cover was recorded with time interval 15 min) using thermal imager Fluke Ti32, and then it was subjected to fractal analyses.

Free Java-based open-source software ImageJ 1.47v and plugin FracLac2014Aprb1012 were used to calculate their fractal dimensions distributions. The way to define both the fractal and the multifractal dimensions of the thermograms was based on the box counting method [6, 7], and a maximum relative error did not exceed 6%. For additional data treatment, a trial version of Wolfram Mathematica has been used. It is necessary to notice, the searching masks for each kernel were developed to optimize the processing of data lists (76800 elements) and reduced arrays (76800/kernel size), that greatly increased time effectiveness.

Results and discussion

Regarding the supply control system of technical water in NPP, that is used to cool the turbine condensers, it is possible to distinguish several groups of objects subjected to safety inspection: buried pipelines, stop valves, pumping facility, facilities of spray ponds. The surface temperature was successfully determined under the control mode of valves. We succeeded in finding of several painted coating peeling in initial stage. Investigations were conducted at ambient temperature 25°C and 2°C, the approximate temperature of water was 15°C. Obviously, the defects detection was more effective at lower temperature at night than at a daytime. For example, the thermogram of spray ponds shields is presented on Fig. 1.

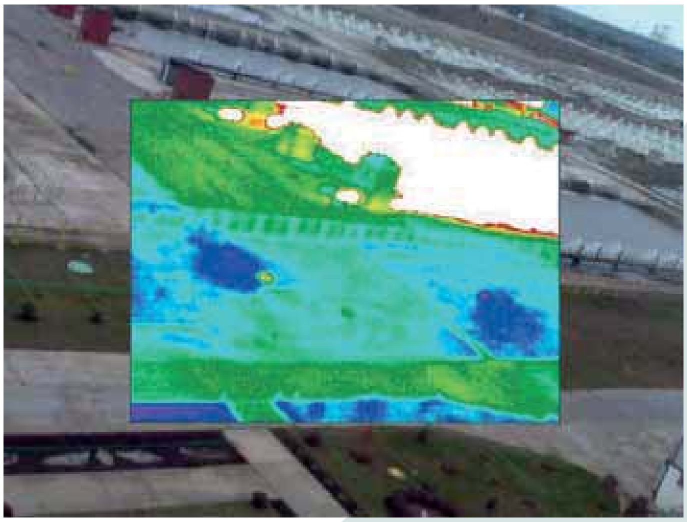
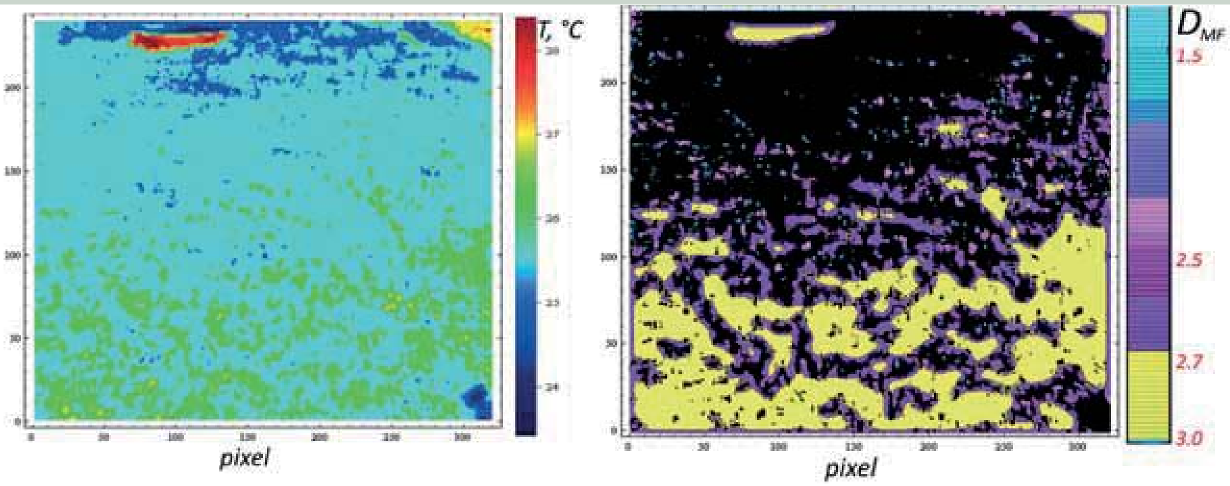


Fig.1. Thermogram of spray pond and corresponding temperature distribution on its surface

The most complex feature is the integrity testing of buried pipelines because of inflation pressures at is not enough for using of ultrasonic leak testers, especially for low pressure pipelines which carries water form spray bonds. In the case of leakage formation and moisture aggregation at the surface, the distortion of the heat distribution is detected directly by thermal techniques as for instance in [9]. The situation may be complicated by the pipelines that are buried underground or placed at a level of ground waters. In this case, the distortions occur by the evolutionary way: soil washout, shift of moisture transfer regime, which can become apparent as changes of surface micro relief. Such heterogeneity of coating as concrete slabs, crushed stone, asphalt and greenery may also influence on the detectability of the heat heterogeneity. In our study, extensive temperature gradients which can be linked to the failure weren't observed in the inspected facilities.

Next, fractal analysis was applied to enhance informa-



a b

Fig.2. a) illustrates a thermogram of the soil surface with a grass cover and local temperature heterogeneity. This thermo-gram is initial in a sequence, t= 0 min. (b) represents a raw distribution of multifractal dimension calculated by box counting method in FracLac. Black color - background

tivity of thermograms. In general, fractal dimension of thermal image depends on its visualization type. If we consider a thermogram as a binary image, its fractal dimensions ranges from 1 to 2, it has two possible values each pixel. If the thermogram is represented as a grayscale image, then it is a 3-dimensions object, each pixel *(x, y)* has intensity *z=f(x, y)* with 256 possible values. In the latter case, the thermogram is a surface and its corresponding fractal dimensions ranging in an interval from 2 to 3. The color thermogram is a hyper-surface in a color space [4-9]. In this research, we only used the grayscale images. However, due to the physical principles of infrared cameras, then some binarization of thermograms may be required to filter a feature of interest.

We conducted the multifractal analysis and local connected fractal dimension analysis of the sequence of three thermograms of the soil surface with grass cover and of the grayscale raster images of their deviations d_{ij}. The initial thermogram (t = 0 min) and the calculated fractal dimension distribution are presented on Fig. 2. Fractal characteristics of d_{ij} distributions were also calculated for low and high abmodalities. Having filtered the obtained data from the noise, the obtained results were shown on Figure 3. It was found, that the fractal dimensions of the thermograms D_{MF} are smaller than the fractal dimensions of their local temperature deviations (deviations in a kernel of 4 x 3 size). The variation of the D_{MF} intervals (~ 0.1) is caused by the disadvantages of the oblique imaging, camera tilt, low matrix resolution and the surface heterogeneity. The higher D_{MF} for local deviations is explained by the influence of local thermal heterogeneities detected during thermographic monitoring. Only small fluctuations of fractal dimensions with time were found in the acquired series, which means that no significant change of environment was noticed and underground pipelines are in proper condition. This approach is selected for future monitoring tests in order to detect equipment failures.

Next, the influence of resolution on the statistic fractality was studied. After the reduction of resolution of thermograms (e.g., Fig. 4 represents a reduced thermogram for a kernel *4x3*) using arithmetic averaging over a kernel, both the temperature distributions and the multifractal dimension intervals were changed significantly. The corresponding fractal dimension intervals decreased with reduction of image resolution, i.e. with an increase of the averaging kernel size (see Fig. 5). This effect was expected, because the local complexity with the reduction of resolution should deteriorate.

The dependence of fractal scaling characteristics on a kernel size for filtered deviations was also investigated. The imposed conditions on deviation were: we take into account only those pixels which abmodality in a kernel does not excess or it is higher than the absolute accuracy at measuring temperature ~0.05K. It was shown (Fig. 6, 7), that the filter condition changed the dependence to the opposite. First, if the filter condition is $\Delta = |T_{i,j} - \overline{T_{kl}}| \le 0.05$K, then the multifractal dimension decreases with an increase of a kernel size (Fig. 6).

If the filter condition is $\Delta = |T_{i,j} - \overline{T_{kl}}| > 0.05K$, then the

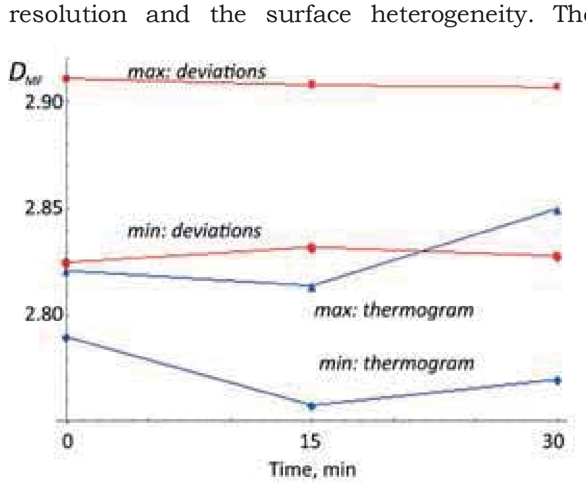


Fig.3. Filtered multifractal dimension intervals (min and max values) D_{MF} for a sequence of thermograms (3 steps x 15 min) in red. D_{MF} intervals for local deviations in blue, calculated for a kernel 4x3

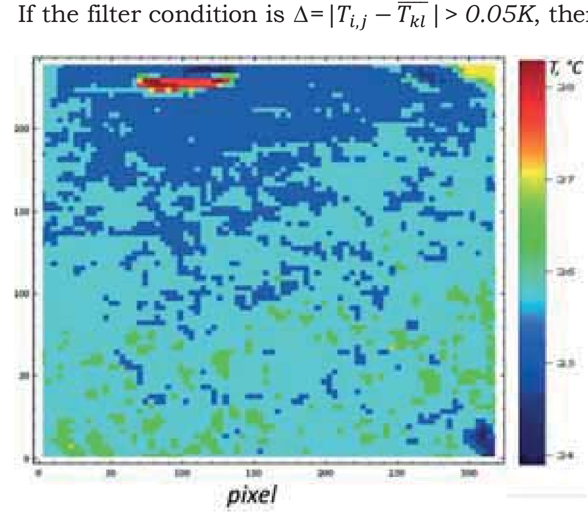


Fig.4. Image of thermogram of the soil surface with a grass cover (t = 0 min) with reduced resolution for a kernel size 4x3.

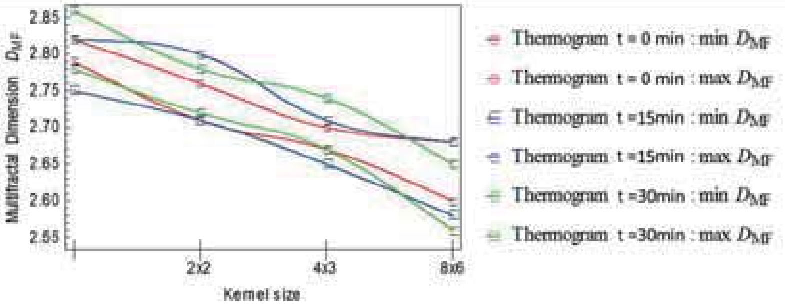


Fig.5. Dependence of the min-max ranges of multifractal dimension D_{MF} on a kernel size for the time series of thermograms of the soil surface with a grass cover.

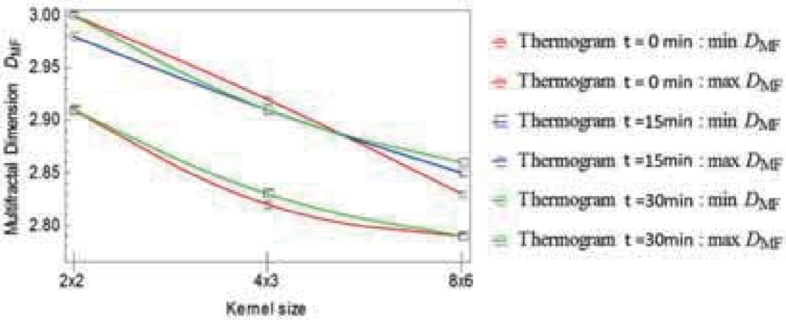


Fig.6. Dependence of the min-max ranges of multifractal dimension D_{MF} on a kernel size for the filtered local deviations of the time series of thermograms. Filter condition: $\Delta = |T_{i,j} - \overline{T_{kl}}| \le 0.05K$.

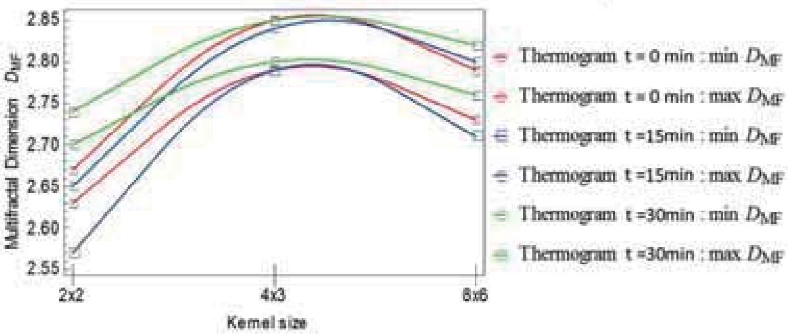


Fig.7. Dependence of the min-max ranges of multifractal dimension D_{MF} on a kernel size for the filtered local deviations of the time series of thermograms. Filter condition: $\Delta = |T_{i,j} - \overline{T_{kl}}| > 0.05K$.

multifractal dimension increases with an increase of a kernel size (4x3) and then decreases (at 8x6) under the influence of data degeneration (see Fig. 7). Such behaviour of D_{MF} is explained by the segmentation of data - if $\Delta \le 0.05K$ we investigate small local changes in temperature, while $\Delta > 0.05K$ – we consider the extremal differences in temperature variations of thermograms. However, the latter phenomenon must be confirmed in future for other data sets to avoid ambiguities.

Next, the influence of random noise on the acquired thermograms was studied. A random noise with amplitude of 0.05 K (standard absolute accuracy of measurements) was added directly to the thermograms, but significant changes in the fractal scaling were not observed. Addition of the low-intensity noise to the thermograms led to blurring, and the allocated pixels in thermograms were randomly distributed. Applying such procedure, we also tested the disturbance of the thermographic monitoring with the noise of amplitude up to 0.25 K. As the result, 5% narrowing of the fractal dimension intervals occurred. So, we can conclude, that the fractal dimension distributions are stable to a small additive noise. It was found, that a fractal dimension distribution spectrum of certain data set can be filtered over defined range of D_{MF} and then it can be extrapolated to the raw thermographic data set to define a corresponding feature of interest. In such way, noise or any feature of interest defined in a fractal spectrum can be allocated to certain area in a thermogram for further recognition. At present moment, a special software package is under development to automate this method. This is of great importance for further application for detection and recognition of leaks, thinning, corrosion of the pipelines in the industry.

Conclusions

This work presents the results of the thermography monitoring performed at the nuclear power plants in Ukraine. It is confirmed, that it is reasonable to set the stationary points of observation and analyze dynamics of parameters that characterized temperature field to provide early diagnostics of the developed leakage, to detect temperature anomalies in the equipment, especially, in the underground facilities. As a complementary method to treat the data of thermograms, it is recommended to apply fractal analyses. It was found, that fractal analyses are sensitive to local variations of the temperature field, while they are robust for noise with the amplitude up to 5 times higher than an accuracy of measurements. Quantitative characterization of the fractal complexity of the thermographic data complements the conventional statistical analysis techniques and it provides additional insight into the problem of heat dissipation and IR monitoring. Better understanding of the fractal character of thermograms will enable the engineers to provide guidance for detection and recognition of the heat heterogeneities at the industrial facilities.

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