EXPERIMENTAL RESEARCH OF LIMITS FOR THERMAL MODULATION TRANSFER FUNCTION

by

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The paper presented testing of surface defects by pulse video thermography techniques. Such techniques rely on transient infrared radiation from the sample heated by the short duration flux initiated by flesh. Experimental measurements are realized by infrared sensor (FLIR camera). Testing results are considered for the samples with controlled designed defects beyond observed surfaces. The effects of response through the transparent wall are measured as infrared visible radiance. Researches with controlled samples are performed to verify visibility threshold of defect dimensions and forms, for possible use as modulation transfer function of defects hidden beyond the surfaces of thin metal walls. Dimensionless coefficients are derived for method estimations as the results from experimental research.

Key words: *pulsed video thermography, infrared sensors, thermal imaging, modulation transfer function*

Introduction

The pulsed video thermography measurements, as the method, has actual and different interests in applications since it was introduced 1961 year, and editted in the papers, Parker *et al.*, *e. g.* [1, 2]. The basic advantage of the method is to measure small temperature differences detected as radiation on the measured surface. These radiations are consequences of heat distributions at the opposite side of surface initiated by light pulse, on the samples with thin walls.

Back side of thin wall samples, with defects, cracks, splits or other material disturbances transforms injected heat energy of light pulse, and changes temperature field in the thickness of the wall, making it possible to recognize on the front wall surface by infrared (IR camera). Thermo physical properties of the sample material such as thermal diffusivity, reflection coefficients from the surface, heat capacity and thermal conductivity can be obtained before pulse initiation process, by some other method.

In early papers Deem *et al.*, *e. g.* [2, 3], this method has different names, for example impulse radiometry, pulsed video method *etc*. Reference [4], gives measurement techniques review for thermal physical properties of materials including luminous pulse non-contact measurements. Papers of Tam *et al.*, *e. g.* [5], and Leung *et al.*, *e. g.* [6], have developed this method by theoretical approach in detail analysis of infrared (IR) signals reflected from the sample to IR detector. In the papers of Reynolds *et al.*, *e. g.* [3], and Milne *et al.*, *e. g.* [7], the term pulse video thermography (PVT) is mentioned for the first time and is usually taken in the further papers. In the papers [8-12], is given detail review of non-destructive thermal diagnostic. Mandelis and numerous other authors used photothermal radiometry method for detection of surface and subsurface defects. Approval for PVT method detection of defects or cracks beyond the surface is basic advantage of this method that gives opportunity for other applications.

Similar as presented in literature, *e. g.* [2, 13], this paper experimentally considered possibilities for threshold sensitivities of IR system testing and evaluation of splits and channels, as defects. One possible application of PVT methodology could be recognition of code information beyond the wall of product. The initial plan of experimental work was to test threshold, possibilities of detection defects composed in the form of barcode (modulation transfer function). The concept of modulation transfer function (MTF), well known in optics, is possible to apply as new control concept if tested sensitivity by PVT imaging satisfies appropriate visibility beyond the observed surface. Actual and former applications of different non-destructive testing sublayers of coated materials on experimental samples, evaluated some knowledge of sensitivity on defects, cracks, and splits formed beyond radiated surfaces. The tested structure of defects considered of splits with different widths and depths on the fixed distances, in the first approximation. Sample material was aluminum, for the beginning, as the most frequently used for light designed constructions. Basic form of samples, for threshold performances testing, is taken as the smooth plate with defects beyond its surface. The inspection of surface evaluated by thermal contrast that appears above splits, cracks, and defects, of controlled dimensions beyond the surface, can approximately give empirical estimations of threshold sensitivities analyzed by IR images. Measuring temperature with IR cameras of high performances, such as FLIR, provides high scene resolution, good enough for estimations in new applications. This method could satisfy MTF necessities, under controlled and determined conditions. Accuracy of measuring temperature this way requires the knowledge of thermal diffusion process through the material and thermophysical properties of observed sample, tested before, by simulation or by previous experiments. This job has been done earlier and referred in the papers, *e. g.* [14, 15].

Theoretical basis of the method

Basic physical principle of PVT method is conversion of absorbed electromagnetic energy, generated by the light pulse on the surface into the heat. This generated heat energy is conducted through the wall thickness changing absorbing surface radiance depend of structure in the wall thickness. Heat conduction along the wall thickness is considered by 1-D model shown on the cross-section A-A, fig. 3. One-dimensional model is valid usually when dimension of light (illumination) spots on the surface front side are big enough comparing to the heat penetration direction x by depth. In papers [16, 17], heat diffusion time is derived through the thickness sample illuminated by Dirac pulse function of form represented in fig. 2. Mathematical interpretation is also given in approximate form in fig. 2. Time of the thermal diffusion is representative theoretical parameter as the basic value of detection frequency treatment by 1-D method of heat conduction through the wall of semiinfinite plate. Paper [8], in detail discovered threshold frequency performances of detection for photothermal radiometry (PTR) signal on the aluminum samples with approximate thickness of 2.5 mm for which 1-D model is applicable. This approval is experimentally checked by appropriate measured error. Values of threshold frequencies are dependent of ratio between perimeter of illuminated surface and wall thickness responsible for 1-D heat conduction. Ref. [8], shows satisfying assumptions of 1-D heat conduction, if ratio of illuminated surfaces perimeters and wall thicknesses is about 2-6. That corresponds to the detection frequencies of 90-20 Hz, and time domains of 11.1-50 ms, calculated for minimum and maximum of mentioned ratios. In this paper ratio between homogenous illuminated surface perimeter and sample wall thicknesses is about 25-15. This value is much greater than ratios represented in experimental work in ref. [8]. Higher values of this ratios understood higher values

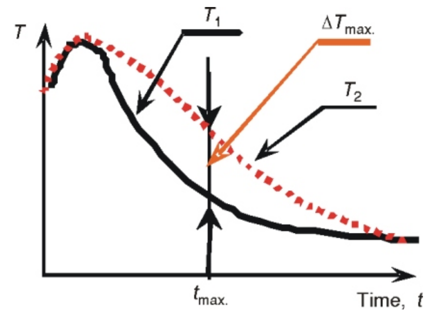

Figure 1. Typical temperature decay in time on the surface of sample

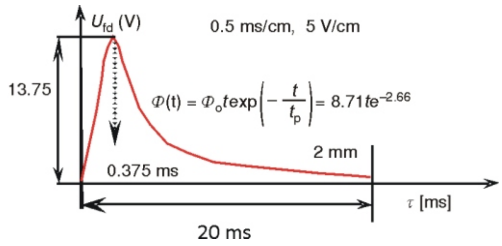

Figure 2. Luminous (light) flux in time

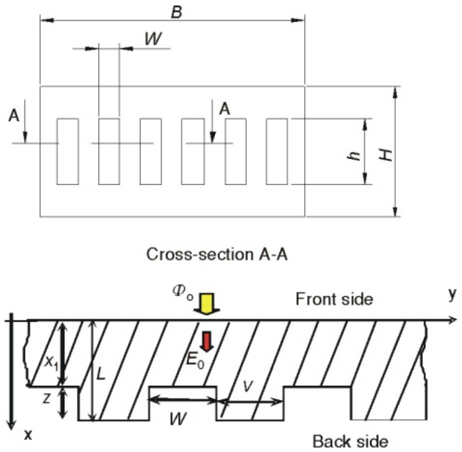

Figure 3. Sample model

of threshold detection time domains for 1-D treatment of heat conduction with appropriate satisfying errors. That means correct approximation for 1-D treatment of heat conduction. In experiments on the samples representative in fig. 3, according with references [16, 17], calculated time domain from 1-D model is about 1.1-17.1 ms. This corresponds to conclusion from ref. [8], that detection time for aluminum samples of similar thicknesses has to be less than 20 ms. Heat pulse along thin wall thickness is changing through the depth of penetration in sample along direction x, fig. 3, by uniform distribution. *e. g.* [18]. Under all these conditions, mentioned above, general solution of Fourier's equation, *e. g.* [17], can be approximated with 1-D temperature field. Heat flux, as the part of luminous light energy E_0, penetrates through the sample depth, changes heat density around the defects and making an inhomogeneous field distribution of scene radiance. The layer above the defect has higher temperature T_2 than thickness without defects T_1. Time profile of temperature distribution is shown on curves 1 and 2, fig. 1. According to, *e. g.* [13, 15], temperature profiles solutions, in the thickness of heat injection, above defects and behind them, are not the same, and are given by expressions:

$$T_1 \quad \frac{E_0}{\rho C\sqrt{\pi a t}} \exp \quad \frac{x^2}{4at} \tag{1}$$

$$T_2 \quad \frac{E_0}{\rho C x_1} \; 1 \quad 2\exp \quad \frac{\pi^2 a t}{x_1^2} \quad 2\exp \quad \frac{4\pi^2 a t}{x_1^2} \quad 2\exp \quad \frac{9\pi^2 a t}{x_1^2} \tag{2}$$

Temperature differences *vs*. time, eqs. (1) and (2), *i. e*. the differences expressed on the curves 2 and 1 in fig. 1, reach maximum value on the surface of the sample in the given moment of time $t_{max.}$. These values can be measured with suitable IR sensor, with appropriate resolution and frequency of images sampling. This theoretically demands modernization of new IR sensors types. High sensitive IR sensor is able to detect all spots on the surface that have described heterogenic heat conduction and temperature differences ΔT. Its temperature resolutions became more sensitive than 0.1 °C.

In the case of equilibrium with environmental temperature, radiance of scene indicates homogenous emissivity of inspected surface. The mathematical model of 1-D heat conduction can not completely describe radiance on the surface above defects. It is approved by many experiments, *e. g*. [1-3, 5-7, 13, 18-21], where defect's width and shape disturb 1-D model of heat conduction due to lateral heat conduction and distribution. That is the reason why limited defects can not be treated only by depth, but also by its shape and its width. This fact is key practical question that contributes the possibilities of PVT method to be used for modulation transfer function.

In [10, 11], application possibility of photothermal techniques for thermophysical features characterization, on semitransparent materials besides experimental installation modification and procedure, are also presented. In [9], 1-D laser model IC PTR on composite materials application is also presented. Multilayer composite materials demanded special modulation system to achieve required multilayer structure detection with different thermophysical characteristics and different thickness.

Specimen thickness treatment can be introduced as function of homogenous lighted surface and observed specimen thickness. 1-D heat conduction model application depends on thickness and its marginal value is determined by detection time characteristic in proportion with specimen thickness, squared. Samples of higher thickness are harder to achieve conditions for 1-D treatment because their detection characteristic time goes to higher values for materials with certain thermophysical properties [8]. Marginal defect z depth and its width W besides time-frequent conditions depend on thermodiffusion *i. e*. on material specimen what will be shown in this work and in [14]. Each of these relative relations *i. e*. defect depth in relation to the sample thickness z/L as well as defect width in relation to the defect thickness W/L can be reduced generally to characteristic time detection value with 1-D model treatment possibilities.

Description of experiments and performances of experimental equipment

The sample model used in experimental testing of scene radiance with splits that could be designed as code for MTF (surface with defects) is shown in fig. 3. Measurements have been provided through numerous (over 18), samples characterized and presented in papers, *e. g*. [14-17]. In [14], starting experimental results of defect measurements which have known characteristics on Al plate by PVT method application for possible use of MTF afterwards, are given. In [15], theoretical analysis on lighting process, light energy to thermal energy conversion, thermal conduction, and radiation response are also given. Radiation source parameters and thermovision image registration are optimized. In ref. [16], conditions for 1-D heat conduction model and suppositions for 3-D conduction impacts negligence are analyzed. Method for time characteristics detection in relation to 1-D model for finite thickness walls to half-infinite plate is given and simulation for various metal materials is done. In [17], besides other data, experimental installation structure for Al samples analysis is given and intensity and time profile of lighting and thermal flux in function of experimental equipment position for PVT method needs, are determined.

Any particular sample had splits with different depth and widths, and same lengths (fig. 3). Between two defects that simulated splits, of given width W and depth z, there were surface parts without splits, on the same surface width as defects (splits) W. This part of surface had full thickness of samples L (fig. 3). Experimental scheme of the samples, IR camera and pulse radiation source (flash) for initiation splits radiance on the sample surface and positioning of the samples with simulated splits, is illustrated in fig. 4. Distances of tested samples from camera objective and from pulse source, with appropriate angle of 39° to the surface orthogonal line, is also shown. The samples are radiated from the side opposite of the surface by orthogonal pulse in aim to provide transversal heat injection through full thickness *L*.

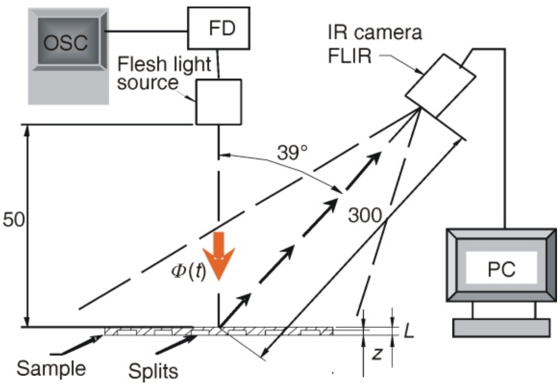

Figure 4. Experimental method setup

Excitation luminous (light) pulse, variable in time, that causes non-steady heat effect over the depth of sample, is given in fig. 2, in the form of measured voltage, equivalent *vs.* time, *e. g.* [14]. Radiated energy from the surface is framed and tracked by IR camera. Experiments started from the shallowest splits (defects) by variation of its widths. Simultaneously evaluation of width and depth dimensions, in tests discovered the influences of lateral heat distribution and errors of assumptions for 1-D heat conduction. Appearing the best and the worst visible samples, had to indicate how lateral heat conduction influenced on radiance in the center line of designed splits on the samples. Basic used experimental set, with appropriate equipment is shown in fig. 4 and in detail explained in *e. g.* [14-17]. It consists of:

(1) Surface treated aluminum samples, shown in fig. 3 and described above in this chapter. Surface treatment has been realized in aim to improve surface radiance visibility in IR domain and to decrease level of noise important for threshold sensitivity temperature.
(2) Foto flash YASHICA CS-250AF is used as a source of light (luminous). Pulse is previously calibrated, *e. g.* [14], fig. 2.
(3) IR camera FLIR ThermaCAM^{TM} P65 7.5–13 mm wavelengths was disposed on the same side with light flash source, at the minimum angle for possible technical positioning. The quality of images sampling depends of IR frequency framing possibility which was by time characteristic about 40 ms for one frame.
(4) Equipment for automatic tracking of images and its digital acquisition using PC computer with appropriate software, standardized by FLIR equipment.

Analysis of the results

Visibility criteria of temperature contrast are accepted on non-pulsed scene radiance with temperature resolution 0.5 °C as threshold visible differences as noise.

- The analysis of the medium deep defects of ½ thicknesses on the samples is visible only on widths higher than sample thickness *L*.
- The analysis of the deepest splits *z* on samples with split depth *z* as ¾ of total sample thickness *L* is not visible for split widths *W* less than split depth *z*. The visibility threshold width *W* is on the sample with same level of depth *z* and width *W*. Wider splits with same depth *z* are visible.
- Splits with the greatest width *W*, same as total thickness *L*, are the best visible samples. Temperature resolution for this sample of 1.8 °C, fig. (6), provides excellent visibility by IR sensor. Figures 5 and 6, show the radiances of threshold invisible samples and maximum visible

samples on scene surface. Images (a) are samples before, and images (b) after pulse radiation. Also, graphs (a) and (b), are signals for threshold and for maximum detected resolution of temperature differences. In fig. 6, especially is shown, lateral flux influences of injected pulse energy, distributed through the sample and increases effect, of temperature differences resolution. Image measured for the widest splits, with low depth, indicates that lateral heat

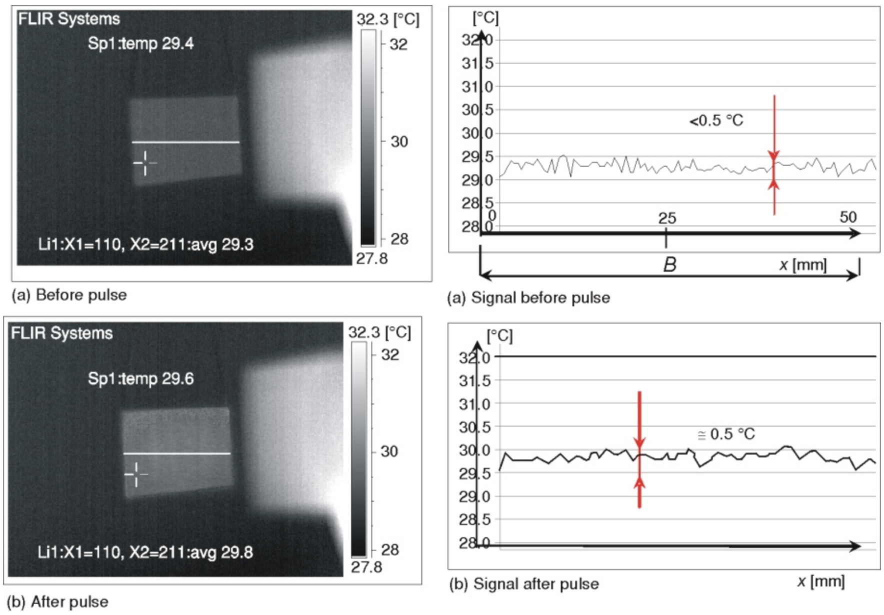

Figure. 5. Minimum visible thermal sensitivity of designed defects

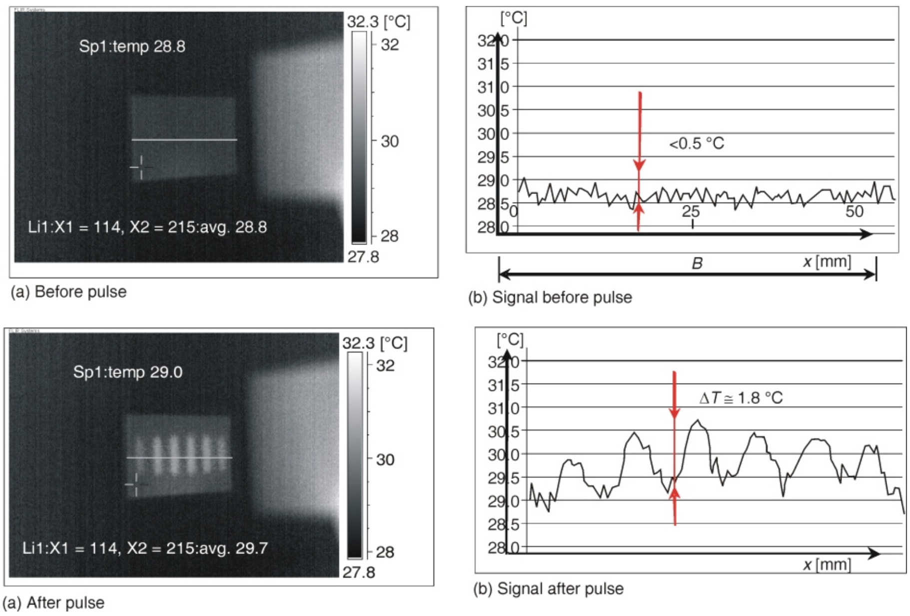

Figure. 6. Maximum visible thermal sensitivity of designed defects

distribution didn't allow temperature changes above splits, more than noise of surface, before pulse, fig. 5. After pulse initiation, in this case, splits were again invisible by IR sensor. Based on developed experimental results and measured temperatures of radiance, conclusion is that only 4 samples represented, *e. g.* [13], satisfied sensitivity criteria of visibility by this method. The deepest splits on the samples increase resolution of visibility about 3 times if width increases about 2 times. This property shows experimental graph of all collected samples with visible splits in fig. 7, *e. g.* [14]. From the diagram in fig. 7, it is possible to express approximate relation of temperature sensitivity, as the function of split widths designed on the threshold visible depths in the form:

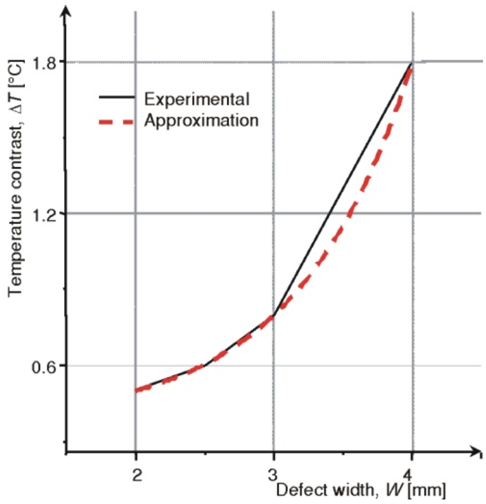

Figure 7. Influences of defect width on method thermal sensitive

$$\Delta T \quad A_1 \exp \quad \frac{W}{0.82938} \quad 0.5 \quad [\ \mathrm{C}] \tag{3}$$

– This experimental equation provides to estimate influences of lateral heat distribution by coefficient of splits width temperature sensitivity K_w. This coefficient can be determined as:

$$K_\mathrm{w} \quad \frac{d(\Delta T)}{\mathrm{d}W} \quad \frac{d}{\mathrm{d}W} \quad A_1 \exp \quad \frac{W}{0.82938} \quad 0.5 \quad 0.014 \exp \quad \frac{W}{0.83} \tag{4}$$

This equation is valid only for this samples and calibrated equipment. Interactive influences of splits (defects), width W and depth z have been considered by assumptions of unknown transversal and lateral heat fluxes injection and distribution by new criteria. For the relative depth z/L and width W/L of splits it is possible to consider ratio between surface of visible splits, S_rd, on the measured surface, and total surface of splits, S_d, under radiated surface. This relative surface is expressed by:

$$S_\mathrm{r} \quad \frac{S_\mathrm{rd}}{S_\mathrm{d}} \tag{5}$$

If this ratio correlates with heat flux percentage distributed in lateral and transversal side, then method can be expressed by simple ratio coefficient in the form:

$$K \quad \frac{S_\mathrm{r}}{\Delta T} 100\% \quad \frac{\%}{\mathrm{C}} \tag{6}$$

as a value for control of PVT method quality and its possible applications for modulation transfer functions.

According to our testing of temperature contrast, when the value of coefficient in eq. (6) is less than 41, tab. 1, effect of the splits is visible in the form of code lines. If the value of this coefficient is more than 41, the temperature resolution is 0.5 °C (ΔT) and less. Temperature resolution less than ΔT is not possible to consider, because surface radiance, before pulse initiation, has approximate noise of temperature sensitivity about 0.5 °C. After calibration and estimation of measurement sensitivity ΔT and split's relative surface S_r, it is possible to use coefficient in, eq. (6), as first approach for analysis of other possibilities of equipment, samples *etc*. to design MTF function by splits beyond the thin walls.

Table 1. Relative surface S_r and relative sensitivity coefficient (K)

Relative surface, S_r						
S_r	1.05	0.83	0.71	0.59	0.45	0.31
K [% /°C]	28.49	41.32	41.66	41.15	44.64	39.68

Conclusions

The pulsed video thermography measurements (PVT) as the method, has actual and different interests in applications because advantages to measure small temperature differences, detected as radiation beyond observed surfaces of thin layers and thickness. These emissions are consequences of heat distributions at the opposite side of surface initiated by light pulse, on the samples with thin walls. Defects, cracks, splits or other disturbances in material, transforms injected heat energy of light pulse and changes temperature field in thickness of the wall, making possible to recognize beyond wall image on the front wall surface by infrared (IR) camera.

This opportunity, is checked by experiments in aim to be used as modulation transfer function (MTF) for barcode hidden beyond visible walls.

Lateral heat distribution around splits, designed as code lines, is main obstacle to use this application for above purposes. Their margin influences was experimentally checked in this paper. The deepest splits on the samples increase resolution of visibility about 3 times, if width W, increases about 2 times, as the result of lateral heat distribution on the Al samples.

Real use of MTF function would be possible only, if quality estimation of images achieves appropriate technologies. Estimation of splits widths and their distances on the images is the key for successful possible applications. New research has to be undertaken to test automatic image processing and to form threshold pixel visibilities in the given tolerance field. This research has to be performed for different materials and thickness with the best visible form of splits adapted for image processing and recognition.

Dimensionless coefficients K_w and K, derived in this experimental research, shows as initial representatives of splits dimensions ratio and temperature sensitivity influences for the PVT method used in new applications. In this paper attempt was done to set up these coefficients, eqs. (4) and (6), to represent radiance sensitivity on the channel's width changes and lateral heat distribution influences. Coefficients K_w, is derivation of temperature differences by channel width and represents radiance temperature differences sensitivity on the channels width changes, eq. (4). It is not possible to say what can be reached in advance, and if this coefficient would be representative for MTF design. Including this coefficient basic assumptions for correlation between temperature differences and width are archived. Further research has to reveal realization of optimal signal processing estimator for temperature differences, adaptive for splits width estimation, and its recognition. First approach in quantitative estimation – coefficient K_w in, eq. (4), is contribution to evaluate threshold influences for reliable use of 1-D heat conduction model. Coefficient K, eq. (6), represent ratio between surfaces of channels radiance, to the real channel surfaces. It is valid for consideration because of great surface influence in the channels wall thicknesses on the lateral heat conduction. This is, also, qualitative more then quantitative estimator, for the first approach considerations, to approve is it possible or not to design MTF beyond the walls.

Thresholds equipment obstacle is number of frames able to be taken from surfaces during heat radiation of previous illuminated scene, and temperatures differences resolution. Thresholds performance of object is radiance of surface before light pulse, wall thickness, and materials.

Method is possible for coding applications but needs very precise calibration of properties for different objects, appropriate wall thickness, and equipment, accordance with designed dimensions of lines, in the form of beyond wall splits.

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