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(54) **METHOD AND APPARATUS FOR AUTOMATED THERMAL IMAGING OF COMBUSTOR LINERS AND OTHER PRODUCTS**

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(57) **ABSTRACT**

A method and apparatus are provided for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and other products. The apparatus for automated NDE thermal imaging testing of a sample includes a flash lamp positioned at a first side of the sample. An infrared camera is positioned near a second side of the sample. A linear positioning system supports the sample. A data acquisition and processing computer is coupled to the flash lamp for triggering the flash lamp. The data acquisition and processing computer is coupled to the infrared camera for acquiring and processing image data. The data acquisition and processing computer is coupled to the linear positioning system for positioning the sample for sequentially acquiring image data.

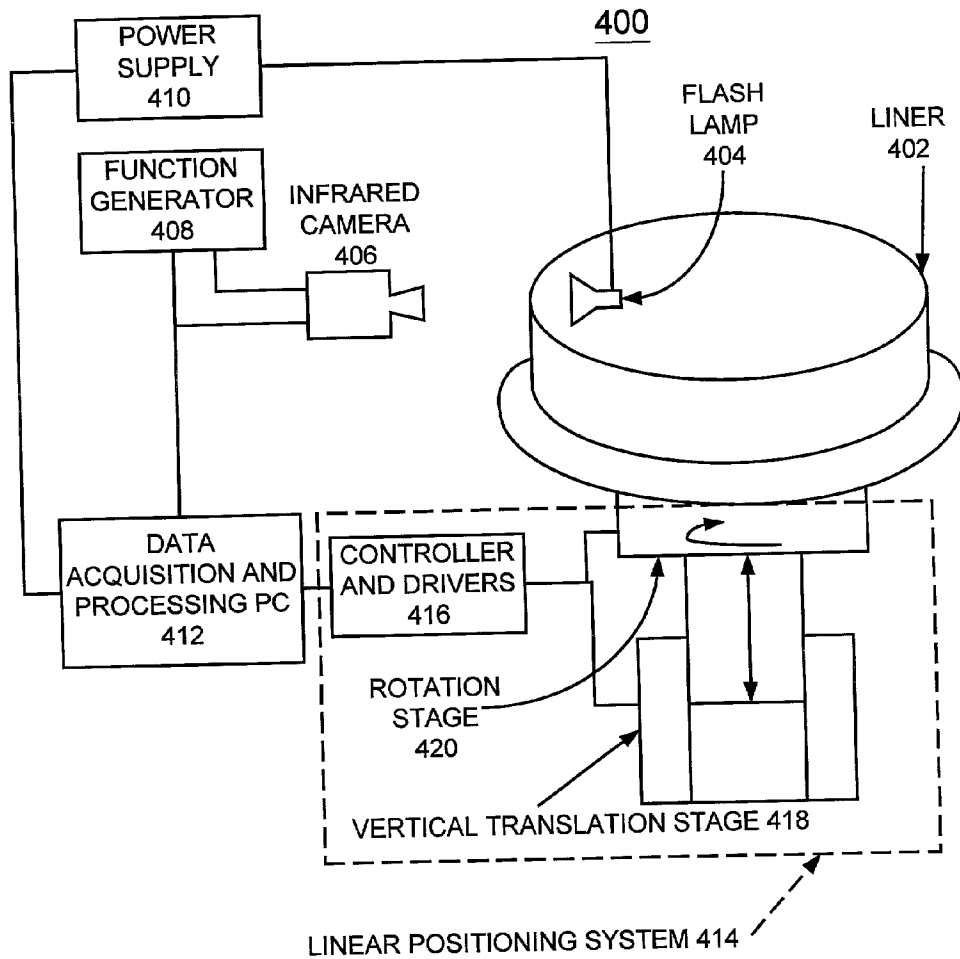
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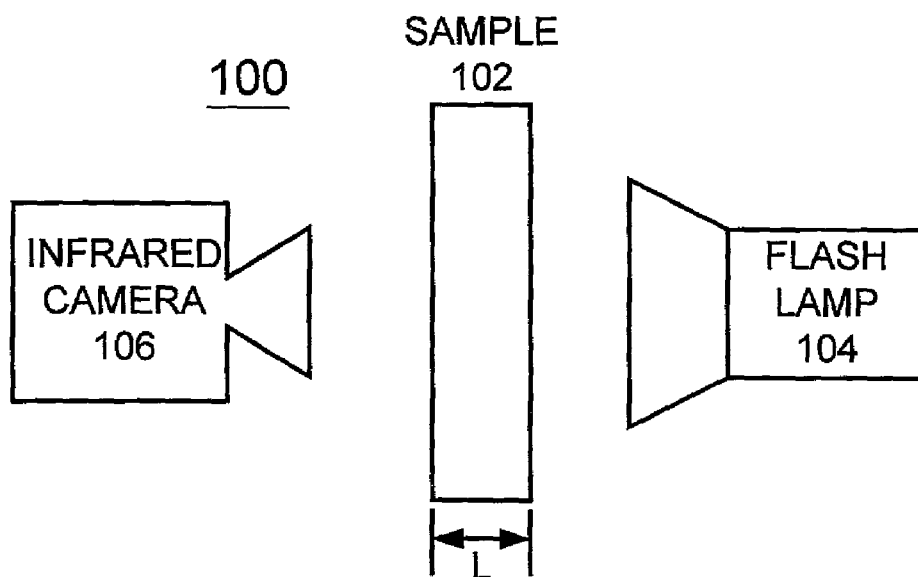


FIG. 1

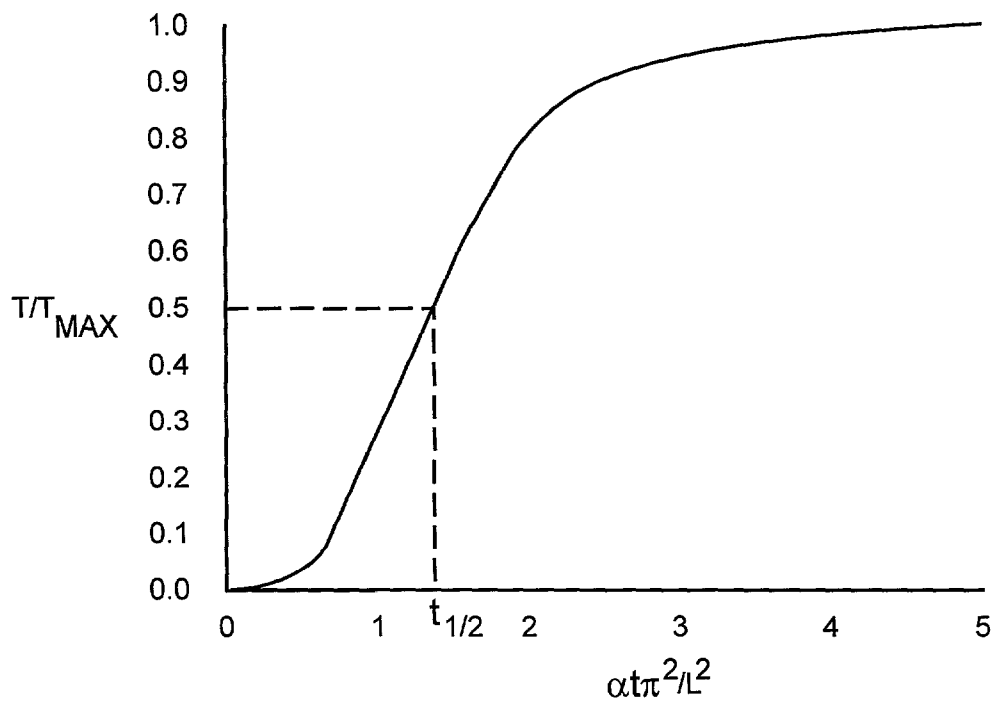


FIG. 2

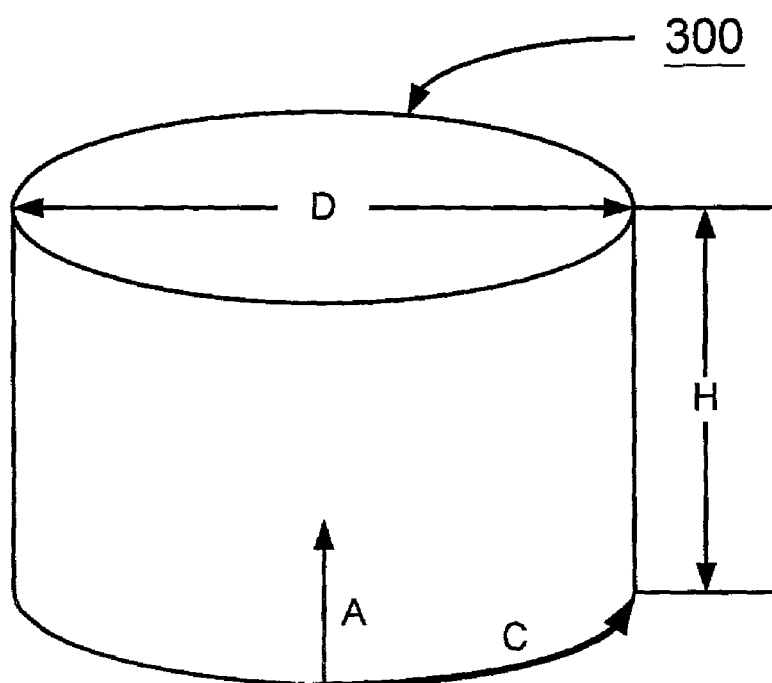


FIG. 3

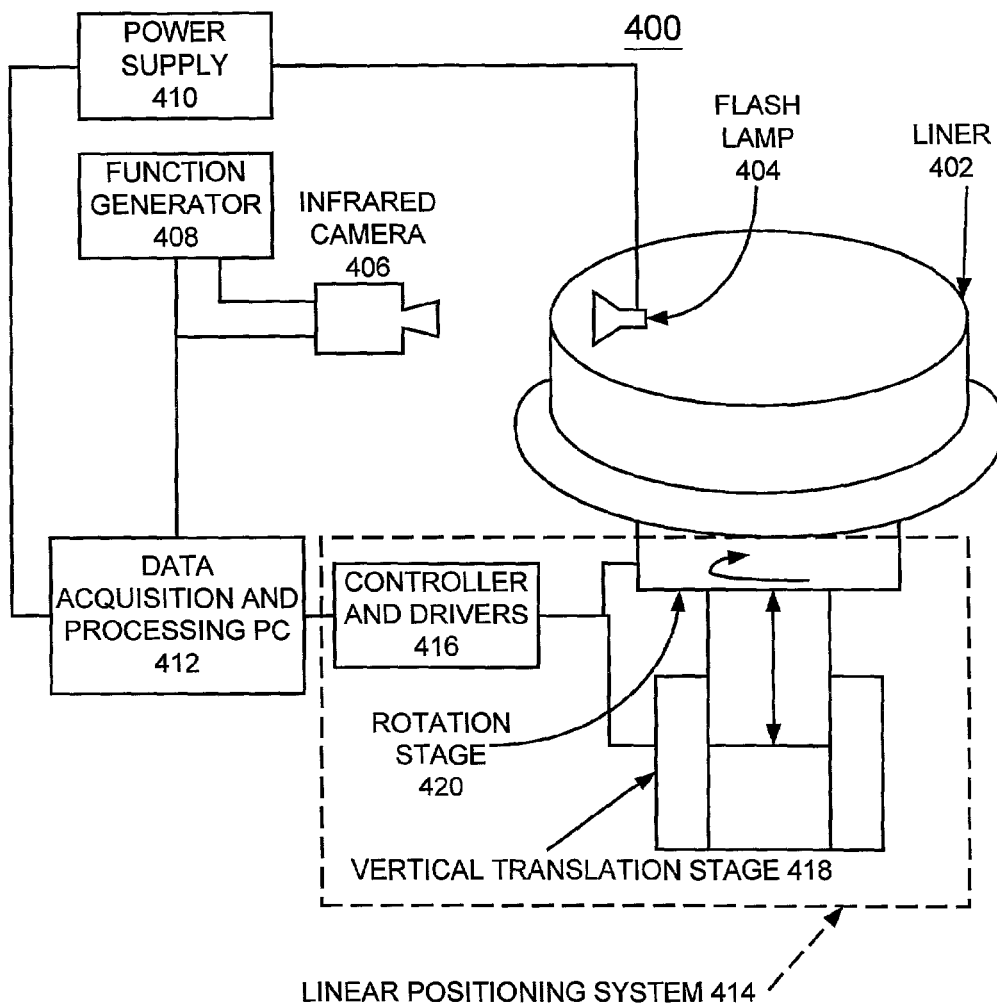
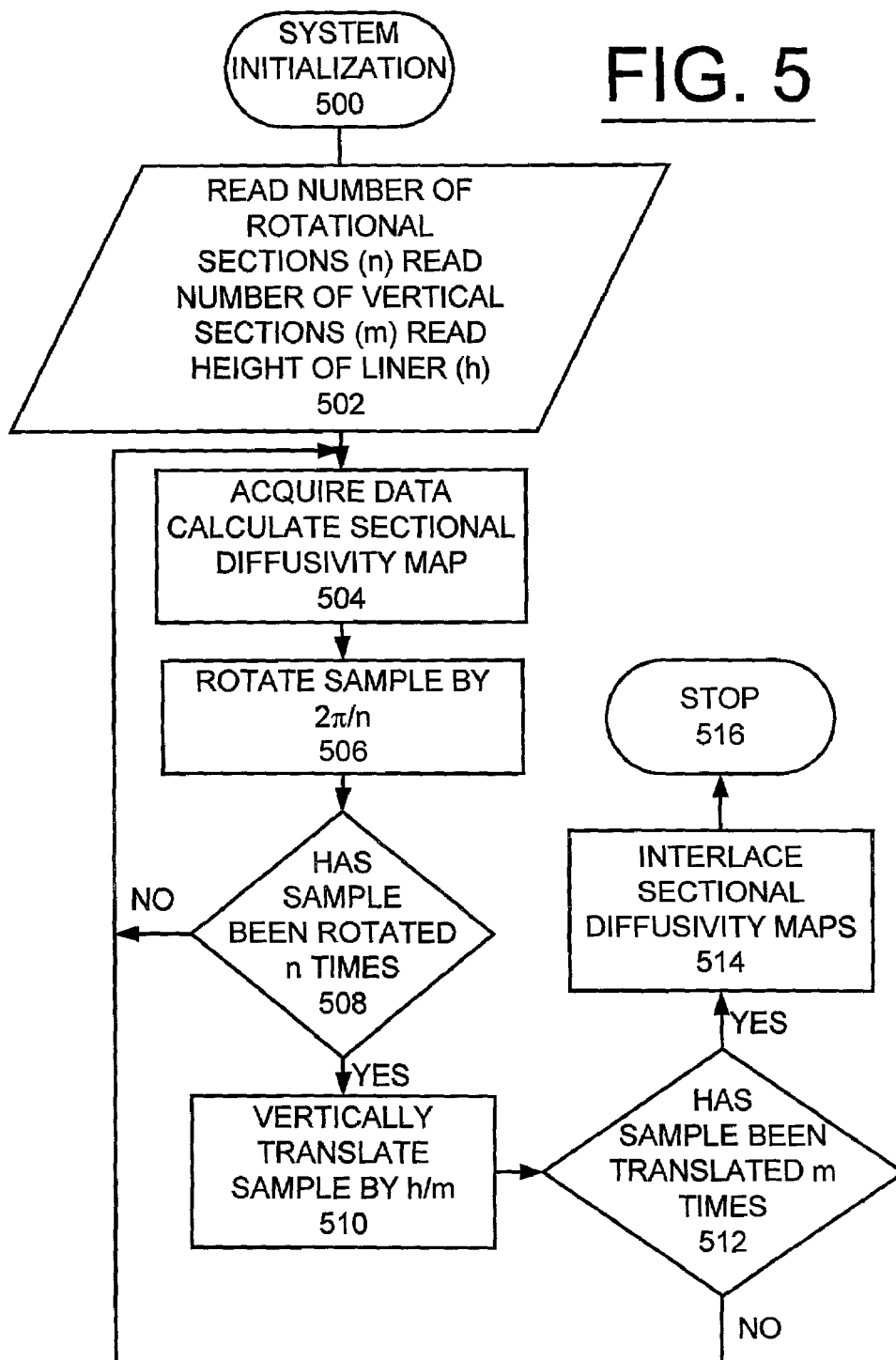


FIG. 4

**FIG. 5**



## METHOD AND APPARATUS FOR AUTOMATED THERMAL IMAGING OF COMBUSTOR LINERS AND OTHER PRODUCTS

[0001] The United States Government has rights in this invention pursuant to Contract No. W-31-109-ENG-38 between the United States Government and Argonne National Laboratory.

### FIELD OF THE INVENTION

[0002] The present invention relates to a method and apparatus for automated thermal imaging of combustor liners and other products; and more particularly, to a method and apparatus for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and other products.

### DESCRIPTION OF THE RELATED ART

[0003] Combustor liners are made at a high cost and are used in severe environments. An advanced ceramic matrix composite (CMC) liner is the single most important structural component expected to be widely used in land and air based heat engines. Because of their high costs, considerable effort has been devoted to characterization during processing to produce defect free components, as well as intermittently during engine operation to assess their lifetimes. Current non-destructive evaluation (NDE) testing is conducted in the laboratory with all testing steps conducted manually. The entire process is very time consuming and sometimes inaccurate, for example, due to misalignment resulting from manual positioning. Combustor liner characterization is critical for manufacturers to improve processing technique. Also combustor liner characterization is important to assess liner lifetime.

[0004] Non-destructive testing using transient thermography which relies upon the transfer of heat through an object over a period of time is known in the art. For example, U.S. Pat. No. 5,711,603, issued Jan. 27, 1998 to Ringermacher et al. and entitled "NONDESTRUCTIVE TESTING: TRANSIENT DEPTH THERMOGRAPHY" discloses a non-destructive testing technique and system using transient depth thermography.

[0005] In known testing arrangements, all steps in the testing are conducted manually, including positioning of the test sample, data acquisition, and data compilation. As a result, considerable time is required for completion of the testing. Also misalignment problems often occur in such manual testing arrangements.

[0006] A principal object of the present invention is to provide a method and apparatus for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and other products.

[0007] It is another object of the invention to provide such method and apparatus for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and other products that is fully automated, generally fast, and accurate.

[0008] It is another object of the invention to provide such method and apparatus for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and

other products that is fully automated and acquires complete combustor liner data without human intervention.

[0009] It is another object of the invention to provide such method and apparatus for automated non-destructive evaluation (NDE) thermal imaging tests of combustor liners and other products substantially without negative effect and that overcome many of the disadvantages of prior arrangements.

### SUMMARY OF THE INVENTION

[0010] In brief, a method and apparatus are provided for automated nondestructive evaluation (NDE) thermal imaging tests of combustor liners and other products. The apparatus for automated NDE thermal imaging testing of a sample includes a flash lamp positioned at a first side of the sample. An infrared camera is positioned near a second side of the sample. A linear positioning system supports the sample. A data acquisition and processing computer is coupled to the flash lamp for triggering the flash lamp. The data acquisition and processing computer is coupled to the infrared camera for acquiring and processing image data. The data acquisition and processing computer is coupled to the linear positioning system for positioning the sample for sequentially acquiring image data.

### BRIEF DESCRIPTION OF THE DRAWINGS

[0011] The present invention together with the above and other objects and advantages may best be understood from the following detailed description of the preferred embodiments of the invention illustrated in the drawings, wherein:

[0012] **FIG. 1** is a diagram illustrating an experimental setup for measuring through-thickness thermal diffusivity image of a test sample;

[0013] **FIG. 2** is a chart illustrating a normalized temperature-time curve at typical point on a front surface of a test-sample with an impulse thermal energy applied to a back surface at time  $t=0$ ;

[0014] **FIG. 3** is a diagram illustrating a combustor liner;

[0015] **FIG. 4** is a diagram illustrating an automated thermal imaging apparatus for NDE testing of combustor liner in accordance with the preferred embodiment; and

[0016] **FIG. 5** is a flow chart illustrating exemplary steps of a method for NDE testing of combustor liner in accordance with the preferred embodiment.

### DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0017] Having reference now to the drawings, in **FIG. 1** there is shown an experimental setup apparatus generally designated by the reference character **100** for measuring through-thickness thermal diffusivity image of a test sample **102**. Experimental setup apparatus **100** includes a flash lamp **104** for providing a pulse of thermal energy for heating a thin layer of material on a first surface, such as the back surface. Experimental setup apparatus **100** includes an infrared camera **106**. The temperature rise at the a second, opposed surface or the front surface of the test sample **102** is continuously monitored by the infrared camera **106** that takes a series of infrared-thermal images to be stored in a computer for further processing. For example, infrared camera **106** sees an area represented by  $256 \times 256$  pixels. After

the flash provided by flash lamp **104**, infrared camera **106** takes a series of images, such as, for example, 50-500 frames.

[**0018**] Infrared thermal imaging is used to measure the full-field distribution through established correlations with known simulated defects in samples having the same thermal diffusivity values. Thermal diffusivity is a material property related to the transient heat transfer speed in the material. A defect such as a crack is a material discontinuity. The crack gap is filled with air and therefore alters, typically reducing heat transfer speed through the material. Advantages of thermal imaging technique include the ability to measure full-field thermal diffusivity distribution, an important thermal property for these materials, and the high sensitivity in detecting defects.

[**0019**] Referring also to **FIG. 2**, the speed of the temperature rise at each pixel of the camera array is determined by a characteristic time, for example, the half-rise time,  $t_{1/2}$ , which represents the time when the temperature rises to one-half of the maximum temperature rise,  $T_{max}$ . **FIG. 2** shows a normalized theoretical temperature/time curve at one point on the front surface of the test sample **102**. The through-thickness thermal diffusivity at this pixel,  $a$ , is then determined as follows:

$$a = (0.139 L^2) / t_{1/2} \quad (1)$$

[**0020**] Where  $L$  is the thickness of the planar sample **102**. By calculating the thermal diffusivity at each pixel of the camera array and then constructing a thermal diffusivity image or map, we can infer the existence and the size, shape, and severity of defects from the thermal diffusivity image.

[**0021**] Referring to **FIG. 3**, there is shown a diagram illustrating a combustor liner **300** having a diameter indicated by an arrow labeled  $D$  and a height indicated by an arrow labeled  $H$ . An axial direction is indicated by an arrow labeled  $A$  and a circumferential direction is indicated by an arrow labeled  $C$ . Consider, for example, a combustor liner **300** having a diameter  $D$  of 8 inches and a height  $H$  of 8 inches, and being 0.15 inch thick and made of advanced ceramic matrix composite (CMC). With an infrared camera **106** consisting of  $256 \times 256$  pixels, infrared sensors, each converting the observed infrared energy in a particular wavelength range, such as, for example  $3-5 \mu\text{m}$  to a digital signal that is related to the intensity of the infrared energy, which is further related to the surface temperature at that pixel, infrared camera **106** can be normalized so that the output signals of all  $256 \times 256$  infrared sensors are correlated linearly with the temperature of the viewed surface. High frame-rate operation of infrared camera **106** is critical in evaluating advanced ceramic matrix composite (CMC) components due to their high thermal diffusivities. Infrared camera **106** can take images at a high frame rate, for example, greater than **120** frames per second with the full array of  $256 \times 256$  infrared sensors at a temperature resolution of less than  $0.015^\circ \text{C}$ . When testing with pulsed thermal imaging, the thermal transient time is usually very short, less than 0.5s, and this must be resolved by the infrared camera **106** in order to determine an accurate half-rise time.

[**0022**] During a flash thermal imaging test, one section or area of a sample surface is examined at a time. After the thermal impulse from the flash lamp **104** is applied, a series of thermal images, for example **100** frames is taken by the

infrared camera **106** and stored in a computer (not shown in **FIG. 1**). These images represent the time history of the temperature change on the front surface of the sample **102**. The through-thickness thermal diffusivity data or map for this section is then determined from equation 1 for every pixel in the image array. To cover the entire sample surface, conventionally the sample is manually translated, either rotationally or linearly, or both.

[**0023**] Surface dimensions seen by the infrared camera **106** determine the spatial resolution of the thermal diffusivity image. If the infrared camera **106** is focused on a surface area of 4-inch by 4-inch square, for example, the spatial resolution represented by each pixel in the image is  $0.156\text{-inch} \times 0.156\text{-inch}$  square with 4 inches divided by 256 sensors in each dimension, or  $0.4\text{-mm} \times 0.4\text{-mm}$  square. Defects larger than this spatial resolution may be visually detected from the image data. For the combustor liner **300** shown in **FIG. 3**, image data would include 2 rows and 8 columns of  $4\text{-inch} \times 4\text{-inch}$  sectional images. For a 30 inch diameter and 8 inch long combustor liner **300**, a typical measurement of its full-field thermal diffusivity requires taking 2 rows and 28 columns of  $4\text{-inch}$  by  $4\text{-inch}$  square sectional images. A complete image of the combustor liner **300** is then compiled from these sectional images.

[**0024**] Referring to **FIG. 4**, there is shown an automated thermal imaging system for NDE testing of a combustor liner **402** in accordance with the preferred embodiment and generally designated by the reference character **400**. Automated thermal imaging system **400** performs a thermal imaging method of the preferred embodiment that is a non-contact, non-immersion, high-resolution and high-sensitivity NDE technique for liner characterization.

[**0025**] Automated thermal imaging system **400** is portable and can be easily set up at laboratories, component processing plants, or engine operating sites.

[**0026**] Automated thermal imaging system **400** includes a flash lamp **404** for providing a pulse of thermal energy for heating a first surface, such as the back surface of the combustor liner **402**. Automated thermal imaging system **400** includes a high-resolution and high-sensitivity infrared camera **406** with  $256 \times 256$  pixel focal plane array of infrared sensors. A function generator **408** coupled to the infrared camera **406** to control the infrared camera and a power supply **410** associated with the flash lamp **404** are operatively controlled by a data acquisition and processing personal computer **412**.

[**0027**] Automated thermal imaging system **400** includes a linear positioning system **414** including a controller and drivers unit **416** coupled to the data acquisition and processing personal computer **412** for operatively controlling a vertical translation stage **418** and a rotation stage **420**. Automated thermal imaging system **400** provides accurate positioning and automated stage motion control with the vertical translation stage **418** and rotation stage **420**. Automated thermal imaging system **400** automatically compiles the entire line image using data processing software for full  $256 \times 256$  pixel image processing in about 10-20 seconds.

[**0028**] During operation of the automated thermal imaging system **400**, first the combustor liner **402** is placed on the



rotation stage **420** and vertical translation stage **418**. The infrared camera **406** is placed outside the liner and focused on a section of the outside surface of the combustor liner **402**. The flash lamp **404** is positioned inside the combustor liner **402** and faces the section viewed by the infrared camera **406**. Then the control program performed by the data acquisition and processing personal computer **412** is initiated. The control program triggers the flash lamp **404** and acquires a series of thermal images with the infrared camera **406** and performs calculations to obtain thermal diffusivity data for the current section. Then the liner is moved in predetermined directions, circumferential, vertical or both with the infrared camera **406** distanced to view the adjacent section for the next data acquisition. The control program of the preferred embodiment automatically allows the process to continue until the entire surface of the combustor liner **402** has been tested. The control program compiles a complete image data of the combustor liner **402** from all sectional image data according to the sequence that the sectional image data was obtained. For a typical 30-inch diameter, 8-inch lone liner **404** with 4-inch×4-inch sections for a total of 54 sections, complete testing takes less than one hour.

[0029] FIG. 5 illustrates exemplary method steps performed by the automated thermal imaging system **400** for NDE testing of the combustor liner **402** in accordance with the preferred embodiment. System initialization is performed as indicated in a block **500**. Next the number of rotational section (n), the number of vertical sections (m) and the height of liner (h) are read as indicated in a block **502**. Image data is acquired and sectional diffusivity map is calculated as indicated in a block **504**. Next the combustor liner **402** is rotated by  $2\pi/n$  as indicated in a block **506**. Checking whether the sample combustor liner **402** has been rotated n times is performed as indicated in a decision block **508**. If not, then the sequential operations return to block **504** and image data is acquired and sectional diffusivity map is calculated. When determined at decision block **508** that the sample combustor liner **402** has been rotated n times, then the sample combustor liner **402** is vertically translated by h/m as indicated in a block **510**. Checking whether the sample combustor liner **402** has been vertically translated m times is performed as indicated in a decision block **512**. If not, then the sequential operations return to block **504** and image data is acquired and sectional diffusivity map is calculated. When determined at decision block **512** that the sample combustor liner **402** has been vertically translated m times, the sectional diffusivity maps are interlaced as indicated in a block **514**. This completes the sequential operations as indicated in a block **516**.

[0030] While the present invention has been described with reference to the details of the embodiments of the invention shown in the drawing, these details are not intended to limit the scope of the invention as claimed in the appended claims.

What is claimed is:

1. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products comprising:

- a flash lamp positioned at a first side of the sample;
- an infrared camera positioned near a second side of the sample;

a linear positioning system supporting the sample;

a data acquisition and processing computer; said data acquisition and processing computer coupled to said flash lamp for triggering said flash lamp, said data acquisition and processing computer coupled to said infrared camera for acquiring and processing image data; and said data acquisition and processing computer coupled to said linear positioning system for positioning the sample for sequentially acquiring image data.

2. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 1 includes a power supply coupled between said flash lamp and said data acquisition and processing computer.

3. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 1 further includes a function generator coupled between said infrared camera and said data acquisition and processing computer for controlling said infrared camera.

4. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 1 wherein said infrared camera includes an array of infrared sensors.

5. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 4 wherein said infrared camera array of infrared sensors includes 256×256 focal plane array of infrared sensors.

6. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 1 wherein said linear positioning system includes a vertical translation stage for vertically translating the sample.

7. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 6 wherein said linear positioning system includes a rotation stage for rotating the sample.

8. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 7 wherein said linear positioning system includes a controller and driver unit coupled to said data acquisition and processing computer; said controller and driver unit coupled to said vertical translation stage for vertically translating the sample and coupled to said rotation stage for rotating the sample.

9. Apparatus for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 1 wherein said data acquisition and processing computer automatically compiles a complete image date of the sample from multiple sectional image data.

10. A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products comprising the steps of:

- providing a flash lamp positioned at a first side of the sample;
- providing an infrared camera positioned near a second side of the sample;
- providing a linear positioning system supporting the sample;

utilizing a data acquisition and processing computer for performing the steps of;

triggering said flash lamp,

acquiring and processing image data from said infrared camera;

sequentially positioning the sample with said linear positioning system for sequentially acquiring sectional image data.

**11.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 10 further includes the step of compiling a complete image data of the sample.

**12.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 11 wherein the step of compiling a complete image data of the sample includes the step of interlacing a plurality of sectional diffusivity maps.

**13.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 10 wherein the step of acquiring and processing image data from said infrared camera includes the step of acquiring image data for an array of 256×256 infrared sensors from said infrared camera.

**14.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 11 wherein the step of acquiring and processing image data from said infrared camera includes the steps of acquiring a series of said image data for said array of 256×256 infrared sensors from said infrared camera.

**15.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 14 wherein the step of acquiring and processing image data from said infrared camera includes the step of calculating a thermal diffusivity data map for each of said array of 256×256 infrared sensors from said infrared camera.

**16.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 10 wherein the step of sequentially positioning the sample with said linear positioning system for sequentially acquiring sectional image data includes the step of rotating the sample a predetermined number of times.

**17.** A method for automated non-destructive evaluation (NDE) thermal imaging testing of a sample including combustor liners and other products as recited in claim 16 includes the step of vertically translating the sample a predetermined number of times.

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