Use of thermal imaging in characterization of ceramic fiber structures

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Abstract. Fibrous bodies that contain open porosity can have a very heterogeneous structure that is difficult to characterize in terms of local flow resistance changes within the same sample. This article presents a method that is applicable for a quick analysis of flow distribution even with large samples. In this first attempt to understand how our flow distribution thermal imaging works, we present how the measuring parameters and the results correlate with sample’s thickness and density. The results indicate that our method can quickly make a distinction between areas that have different flow resistances because of variations in the sample’s density or wall thickness.

1. Introduction
Use of fibrous ceramics is widespread in high temperature applications such as furnace linings [1] and hot gas filter elements [2,3]. In some applications it is necessary to produce an even gas flow distribution within the same product because in the case of uneven flow distribution the product may malfunction. In filtration applications the filtration characteristics [4] and the cleaning of filter elements [5] depend on their structure. In addition, the mechanical characteristics of fibrous bodies are affected by uneven wall thickness and changes in bulk density, which are both difficult to measure.

Conventionally, a permeability measurement [6] is used to analyze the flow resistance and changes in it. While the conventional methods can be reliable and fast to analyze the sample as a whole, they cannot be easily used to find differences within a same sample. Because of this a method better than the conventional flow permeability measurement is needed for local permeability analysis.

Thermal imaging has been used in non-destructive testing before [7] but we have invented another way to take advantage of it. We have noticed that a randomly oriented fibrous structure heats faster in certain areas when hot air flows through it. This takes place due to local differences in the air permeability that in this case is mostly controlled by the wall thickness and bulk density of the sample.

2. Materials and Methods

2.1. Thermal imaging system
Measurement system that we used is presented in figure 1. The system included a thermal camera (FLIR Thermacam PM595), length scale, and an adjustable air inlet. Air was blown through a porous sample while its surface was imaged with thermal camera. Air temperature and velocity was varied in the experiments. Sample dimensions and its thermal diffusivity are presented in table 1.

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2.2. Material

The materials in these experiments were composed of non-oriented, silicate based fibers, and some non-fibrous areas. An example of microstructure of the tested material is shown in figure 2. The fiber dimensions, size of non-fibrous parts, and material compositions are presented in table 1.

The pore characterization was carried out with capillary flow porometry and mercury porosimetry. However the highly heterogeneous pore structure and a large size of the samples rendered the exact characterization of the material very difficult. Table 1 presents the measured pore characteristics.

| Table 1. Approximate material parameters. |
|------------------------------------------|
| **Dimensions**                          | **Composition**                  |
| Length [m]                               | mostly Al$_2$SiO$_5$, CaSiO$_3$ and amorphous SiO$_2$ |
| Radius [m]                               |                                  |
| Wall thickness [m]                       |                                  |
| **Microstructure**                       |                                  |
| Fiber diameter [µm]                      | 1 – 10                           |
| Fiber length [µm]                        | below 1000                       |
| Non-fibrous [µm]                         | 10 – 500                         |
| **Pore characteristics**                |                                  |
| Mean flow pore size [µm]                | 4$^a$                            |
| Average pore diameter [µm]               | 4$^b$                            |
| Largest through pore [µm]               | 39$^b$                           |
| Porosity [%]                             | 80$^b$                           |
| **Thermal diffusivity**                 | @200$^\circ$C [mm$^2$/s]         |
|                                         | 0.3$^c$                          |

$^a$ PMI capillary flow porometer  
$^b$ Micrometrics poresizer 9320  
$^c$ NETZSCH 457 MicroFlash

**Figure 1.** A schematic presentation of the thermal imaging setup.

**Figure 2.** SE-image of the studied fiber structure.
3. Results
Tested samples behaved in two distinctive ways. In the first type ‘striped’ sample, hot air seemed to form stripes in the thermal images along the length of the sample, while in the second type ‘spotted’ sample, large cold and hot spots formed. Examples of the two types are presented in the figure 3. The ‘spotted’ type samples were mostly used in the studies but the ‘striped’ sample was used in the experiment in section 3.2 to show that wall thickness is not the only factor that determines the heating rate in the samples.

![Thermal images of two sample types.](image)

**Figure 3.** Thermal images of two sample types.

3.1. Effect of measuring variables
Preliminary measurements were carried out in order to see how the measuring variables, air temperature and flow velocity, affect the measurement. In figure 4 a same sample is first heated with a standard flow rate and temperature (reference), then with a flow velocity twice as high, then with temperature and flow velocity twice as high, and finally with the air flow from the opposite direction.

| Parameters [°C] / [l/min] | Time [sec] | Temp. [°C] Max/Min/Ave |
|---------------------------|------------|------------------------|
| Ref. 100/500              | 535        | 69/22/56               |
| 2x Flow 100/1000          | 195        | 72/23/53               |
| 2x Flow 2x Temp 200/1000  | 90         | 88/33/63               |
| Flow reversed 200/1000    | 120        | 106/51/70              |

**Figure 4.** Effect of changing measurement parameters. Time is heating time during image capture.

3.2. Correlation of thickness and temperature variations
Thickness changes and a thermal image of a ‘spotted’ sample are presented in figure 5a. Thickness is measured in seven places across the length of the sample. Another thickness correlation is presented in figure 5b where in the ‘spotted’ sample it is obvious that the faster heating rate on the left side is caused by smaller wall thickness and thus higher permeability, whereas in the ‘striped’ sample there is little correlation between the heating rate and wall thickness. In this case the heating rate differences have to be caused by some other factor, such as density variations between the cold and hot areas.
3.3. Correlation of density and temperature variations

Bulk density and a thermal image of a 'spotted' sample are presented in figure 6. Density changes were calculated from weights and volume measurements that were carried out from dissected sample images using image processing methods.
3.4. Correlation of density x thickness and temperature variations

Average thickness and density of a ‘spotted’ sample from the above figures 5A and 6 are multiplied and the result is plotted together with the thermal image in figure 7. This is done in order to find out if this rough estimate of permeability is a function of both the density and thickness. This estimate does not take into account the pore characteristics that will affect the permeability but it still leads to a higher correlation than the ones presented before. This is further discussed in section 4.

![Sample density times thickness and its thermal image aligned together.](image)

Figure 7. Sample density times thickness and its thermal image aligned together.

4. Discussion

First thing to notice in the above thermal images is that certain areas of the samples heat faster. In the section 3.1 we showed that this takes place regardless of the gas injection velocity, temperature, and direction of the gas flow. Together these prove that the heating rate differences are caused by certain characteristics of the sample, not the measuring setup. In order to find the dominant character that determines the heating rate in different areas, we visually correlated the thermal images with the local thickness and density of the samples. In the figure 5b the thermal image of a ‘spotted’ sample seemed to contain hot and cold areas as a result of the variation in thickness of the sample. However, in the thermal image of the ‘striped’ sample, in the same figure, hot and cold areas were seen regardless of the negligible changes in wall thickness. This led us to understand that the thickness is not the only factor that controls the heating. After that we studied how density affects the heating rate and the correlation is presented in figure 6. Visual correlation is a little higher with density than with the wall thickness that indicates that the density dominates the heating rate over the wall thickness in this study.

Yet even with a ‘spotted’ sample the correlation seems to be the highest with the computational factor “thickness times density” that is presented in figure 7. Thus it can be deducted that the heating rate, in our particular experiment, is fixed by the relative flow resistance of the sample that is, at least partially a combination of the samples thickness and density. In this study we examined the samples only in terms of density and thickness changes but it is obvious that also the factors related to pore characteristics have an important role in the flow resistance as is shown by [8]. These characteristics are unfortunately difficult to measure in the heterogeneous fiber bodies.

The measurements were carried out with a relatively cool air and high flow velocity which is especially important if the samples have high thermal diffusivity. With highly diffusive samples the high flow velocity eliminates the possibility of remarkable thermal diffusion [9] through the material which would have an effect on the measurements. In addition to choosing the right measuring parameters, we had samples that had a low thermal diffusivity as presented in table 1. Thus we believe that the differences in the heating rates are solely caused by differences in flow distribution of the
samples. This is simply the cause of more hot air flowing through the areas where the permeability is higher, and as the samples surface is comparatively even the more porous areas heat faster. The highest correlation would undoubtedly be found with the heating rate and permeability as it would also take into account the effect of pore characteristics. This is still to be studied and takes time because the local permeability distribution is difficult to measure.

5. Conclusions

In this article we presented a method for analysing flow distribution with thermal camera and hot gas. With the acquired results we have formed a basis for thermal permeability measuring. Comparing the new method to conventional permeability measurement that includes flow and pressure meters, the new one is faster and can possibly find smaller permeability differences if the measuring parameters are chosen correctly. Another strength of this investigated method, is that it can spot differences within the same sample. Even difficult, highly heterogeneous samples, such as the ones analysed in this article, can be measured.

With a small effort this method could be used for instance to ensure an even production quality in terms of permeability of the product or it could be used to analyse local permeability changes, for instance in filtration applications. Experiments presented in this article were carried out for silicate-based fibrous ceramics having low density and thermal diffusivity. The method would undoubtedly be applicable also for other samples if the ratio between the permeability and thermal diffusivity of the them is high enough. In the case of very low ratio, heat conducting through the sample might affect the results. Even in this case the method might be used if the imaged surface was first coated with highly heat absorbing material such as graphite that would promote the heating caused by permeability in favour of the heat conducting through the sample.

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