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Airflow resistance measurements between room temperature and 800°C

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ABSTRACT

Acoustic properties of porous materials are usually measured at room temperature but in many industries, they are required to provide sound absorption in high temperature applications such as in a Heat Recovery Steam Generator (HRSG), automobile silencers and engine liners. In this paper, the airflow resistance has been measured for Alkaline Earth Silicate (AES) fibrous materials that are intended for high temperature applications. Measurements were made at room temperature to ISO 9053-1 and in a bespoke test rig at temperatures up to 800°C inside a kiln. Above 600°C the thickness of the AES material decreased; hence the measurements reported the specific airflow resistance rather than airflow resistivity. The high temperature tests indicated that it might be possible to assume no significant effect of temperature on specific airflow resistance between 20 and 100 °C but not at higher temperatures. The specific airflow resistance depends on the mass of the sample up to 800°C. Up to 600°C, the dependence is similar but as the AES material begins to crystallize between 600 and 800°C it changes significantly. Regression analysis was also used to establish that up to 600°C the specific airflow resistance is proportional to the absolute temperature to the power of 1.6.

Keywords: airflow resistance, porous materials, high temperature

1. INTRODUCTION

In the building industry, porous materials are often used to provide sound absorption at room temperature. However, other industries have high temperature applications which require sound absorption such as gas turbine exhaust silencers in a Heat Recovery Steam Generator (HRSG), aero engine liners, combustion chambers, automotive silencers. In an HRSG, Alkaline Earth Silicate (AES) porous material is used to reduce sound levels inside the silencers and near to the exhaust area which operate at temperatures between 800 and 1300°C (1). Measurement of the properties of acoustic materials at room temperature is well-established; however there is not usually any information available on how the properties change with increasing temperature. Hence to provide data and facilitate product development on absorbent materials for high temperature applications, the aim was to develop experimental procedures to measure the acoustic properties of AES material at high temperatures. As sound propagation in porous materials is dependent on their resistance to airflow, measurements of this resistance can be used to predict both sound absorption and sound attenuation.

The ratio of the differential pressure, ΔP, (Pa) across a layer of porous material and the volumetric airflow rate, q_v, (m^3/s) passing through the layer gives the airflow resistance, R, (Pa.s/m^3) as

$$R = \frac{\Delta P}{q_v} \tag{1}$$

The specific airflow resistance, R_s, (Pa.s/m) applies to a specific thickness of material and is given by

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$$R_\mathrm{s} = RS \tag{2}$$

where S, (m^2) is the area of the porous material.

For homogeneous materials of a specified thickness it is common to refer to the airflow resistivity, r, (Pa.s/m^2) given by

$$r = \frac{R_\mathrm{s}}{d} \tag{3}$$

where d,(m) is the thickness of the material.

For fibrous porous materials, the resistance to airflow depends on the fibre diameter, fibre shape/type, fibre density, number of fibres per unit volume and fibre orientation (note that the airflow resistivity in the lateral direction can be significantly lower than in the longitudinal direction (2)).

This work aimed to carry out measurements up to 800℃ for HRSG applications, using measurements on three different densities of AES fibrous materials, 64, 96 and 128 kg/m^3 with a nominal thickness of 50 mm. The differential pressure across porous materials at high temperatures is lower than at room temperature; hence it is expected that instead of a single sample, two samples might need to be stacked on top of each other (i.e. to form a double sample) to give a measurable differential pressure.

The only previous published airflow measurements at similarly high temperatures appears to have been by Christie (3) who measured one density of rock wool (80 kg/m^3) at 500℃. In Christie's research (3), the flow velocity through the sample was in the range 1×10^{-2} to 4×10^{-2} m/s. For this material, Christie showed that (a) the airflow resistivity was proportional to the 0.6th power of the absolute temperature in Kelvin and (b) above 400℃, the airflow resistivity increases at a lower rate, and (c) airflow resistivity at a particular temperature did not depend on flow velocity within the range of velocities used. Since, AES material is used at temperatures above 500℃, this research investigated the measurements of airflow resistance at room temperature (20℃) according to ISO 9053-1 (4) and in a bespoke test rig inside a kiln at temperatures from room temperature up to 800℃.

In this paper, section 2 describes the experimental apparatus design for both room and high temperatures. The results for room temperature and high temperature are discussed in section 3. Section 4 gives conclusions on the main findings at room and high temperatures.

2. EXPERIMENTAL APPARATUS

The experimental apparatus for both room and high temperature consists of a specific test rig, differential pressure, flow meter and a pressure regulator. A Furness Control FCS 523 instrument is used to measure differential pressure and airflow rate; this consists of two main parts, a laminar flow meter and differential pressure meter. The laminar flow element has the ability to measure volumetric gas flow rates from 0 to 2 l/min and measures volumetric gas flow rate based on the Poiseuille equation. According to the manufacturer, the device generates a very low differential pressure, while offering little restriction to the flow, typically a pressure drop of 100 Pa at full flow rate at 2l/min; however the maximum temperature that the measuring instrument can withstand is 34℃ such that this needed consideration in the experimental design. The differential pressure device can measure to two decimal places with an accuracy of <0.25%. However, since the airflow meter can only withstand pressure ≤300 Pa, it is necessary to reduce the supply air pressure which is supplied at 1200 kPa and to dehumidify the supply air before it enters the meter. This was achieved with a pressure regulator and air filter.

For the high temperature test rig it was necessary to correct the differential pressure that was being measured at room temperature using temperature measurements inside the test rig and at the differential pressure meter.

$$\Delta P'' = P_1'' - P_2'' = \frac{T''}{T'}(P_1' - P_2') \tag{4}$$

where $T^{''}$ indicates at the high temperature inside the test rig and $T^{'}$ indicates room temperature, T is temperature in Kelvin.

Airflow resistance measurements according to ISO 9053-1 (4) and ASTM C522 (5) require a minimum flow velocity of 0.5×10^{-3} m/s (corresponding to a sound pressure level of 80 dB re 2×10^{-5} Pa in a plane wave) and with the valve it is possible to control the flow to $\pm\ 0.01\times10^{-3}$m/s. As the cross section of the sample holders are all 100 mm diameter, this gives the range of volumetric flow rates as between 0.231 and 0.240 l/min.

2.1 Room temperature test rig

The room temperature test rig was designed to satisfy the requirements of ISO 9053-1 (4) and ASTM C522 (5) using the direct airflow method with controlled unidirectional airflow through the test specimen. In order to visually check the position of the test sample, a transparent material (Perspex) was used to fabricate the cylindrical specimen holder (internal diameter of 100 mm and a height of 200 mm). The differential pressure is measured between the volume of air underneath the sample and atmospheric pressure.

2.2 High temperature test Rig

The test rig for high temperature airflow resistance measurements was designed to give nominally identical results at room temperature to the ISO test rig described in ISO 9053-1 (4) and ASTM C522 (5). The initial aim was to design a test rig to withstand temperatures up to 1000 ℃. A similar test rig design to Christie (3) was used as a starting point with the aim of extending its use above 500 ℃. This test rig consists of a preheater with a packing material to ensure that the air enters the sample at the same temperature as the internal kiln temperature and to provide uniform airflow across the surface of the sample (3). After performing several experiments with different packing material, 50 mm Superwool® Plus Blanket was selected as the preheater material. This material has a high melting point, is mechanically stable with very low shrinkage at high temperatures and is mechanically needled for added tensile strength and surface integrity. In contrast to the room temperature test rig where the differential pressure was measured with reference to the atmospheric pressure outside the test rig, the high temperature test rig needs pressure taps to determine the differential pressure across the sample within the sample holder inside the kiln.

The high temperature test rig is shown in Figure 1 and consists of a cylindrical specimen holder and cylindrical preheating chamber. There is one air inlet, one air outlet, two outlets for the differential pressure measurement and one tapping point for the temperature probe. The specimen holder has two perforated meshes to hold the sample in place and a preheating chamber consisting of an air inlet and a differential pressure meter probe inlet. The specimen holder has a height of 150 mm which allowed vertical orientation of the test rig within the kiln. As the high temperature test rig needed to work up to 1000℃, it was necessary to check whether the length of the preheating chamber might need to be significantly longer than that used by Christie (3) to ensure that the air reached the same temperature as the air in the kiln. The process was modelled using Matlab Simulink software to identify a suitable length for the preheating chamber to achieve the required temperature output. By considering the heat transfer occurs from the kiln to preheating chamber it was found that the required length for the preheater was 250 mm.

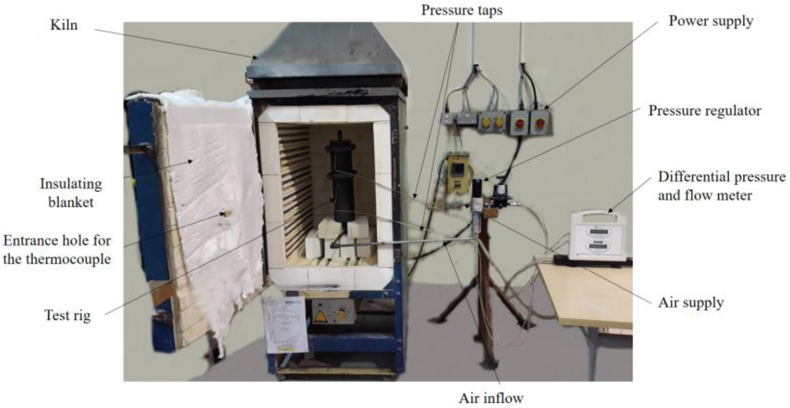

Figure 1 - High temperature test rig assembly.

By considering the material strength and corrosion resistance, Grade 310 austenitic stainless steel was initially selected to fabricate the test rig. However, due to lack of availability of hollow tubes of

Grade 310 austenitic stainless steel and difficulty in machining it, Grade 316 was used instead. As Grade 316 is not designed to withstand such high temperatures, the maximum temperature feasible for measurements was expected to decrease to approximately 900°C. In order to assess the thermal stability and the thermal stress at 900°C, Finite Element Analysis (FEA) was carried out for the high temperature test rig design using Autodesk Mechanical Simulation software. Thermal stress is simulated by coupling transient heat transfer and structural analysis. However, the results showed that Grade 316 austenitic stainless steel design would fail at temperatures near 900°C; hence the upper temperature for all measurements with the high temperature test rig was reduced to 800°C.

The next step was to avoid heat damaging the measurement instruments which cannot withstand the air temperatures generated inside the kiln and to avoid heat conduction via the pipes melting the connections to the measuring instruments. Fortunately, pre-tests showed that the air temperature at the measuring instrument was below 34°C. Hence, there was no need to use a heat exchanger.

3. RESULTS

3.1 Room temperature airflow resistance results

3.1.1 Comparison of the ISO and high temperature test rigs

At room temperature (20°C), a comparison is made to check that the high temperature test rig gave nominally identical results to the ISO 9053-1 test rig. The reason to use different density materials is that the test sample holders are different and therefore ‘soft’ (low density) and ‘stiff’ (high density) samples might be fitted differently in the two test rigs. This is partly due to the ISO rig being transparent which allows the experimenter to see the fitted sample (which is not possible with the high temperature rig) and partly due to the different length of the sample holder tubes.

The average results for ten single and double samples at room temperature are shown in Table 1 indicating the increase in airflow resistivity with increasing density. The coefficient of variation (CoV) is highest for the low density material and could be due to distortion of these soft samples when positioned in the test holder or due to larger variation in the physical properties between samples. For single samples, ANOVA tests indicate significant differences ($p \leq 0.05$) for the 64 and 96 kg/m^3 materials and non-significant differences ($p > 0.05$) for the 128 kg/m^3 material. The significant differences could be due to different fixing and/or compression of the ‘softer’ samples in the test rigs. The ISO test rig is transparent which allows a clear check on the sample position and therefore the fitting for air tightness is expected to be better with this test rig than with the opaque high temperature test rig.

The CoV values for all double samples are lower than the corresponding single samples, particularly for the low density material due to the mixing of two different samples of this more variable material. The lower CoV is beneficial as it allows for a more reliable comparison of the ISO and high temperature test rigs. In theory, the airflow resistivity for single and double samples should be the same if the fitting and compression of the samples inside the sample holder is identical. However, double samples were found to be more compressed than single samples. Therefore, statistical comparisons were carried out using the average airflow resistivity from single and double samples (same batch of material) and the results indicate that there is a statistically significant difference ($p \leq 0.05$) between single and double samples. This is attributed to the different fitting of the samples in test rigs.

Table 1 – Airflow resistivity measurements at room temperature in the ISO and high temperature test rigs.

Single or double samples	Bulk density (kg/m^3)	ISO test rig				High temperature test rig			
		Average thickness (mm)	Average airflow resistivity (Pa.s/m^2)	Standard deviation (Pa.s/m^2)	CoV (-)	Average thickness (mm)	Average airflow resistivity (Pa.s/m^2)	Standard deviation (Pa.s/m^2)	CoV (-)
Single	64	44.2	10,373	983	0.094	47.4	7,940	1158	0.146
Single	96	49.6	36,479	706	0.019	38.5	37,448	624	0.017
Single	128	46.2	102,016	6710	0.066	47.8	107,102	2349	0.022
Double	64	95.5	10,106	331	0.033	88.3	9,961	581	0.059
Double	96	80.8	37,312	605	0.016	78.1	37,766	394	0.010
Double	128	90.4	103,145	4879	0.047	90.7	105,284	1948	0.019

3.1.2 Regression analysis

A linear relationships between airflow resistivity and bulk density is established by considering the logarithm of both parameters as carried out by Nichols (7). Regression curves were determined from the two test rigs using the three material densities and single and double samples as shown in the Figure 2. One-way ANOVA for the two regression models show that there is a statistically non-significant difference ($p>0.05$) between the intercepts and gradients for the two different types of rigs. For the combined dataset for single and double samples it is concluded that the measured airflow resistivity does not differ between the two test rigs.

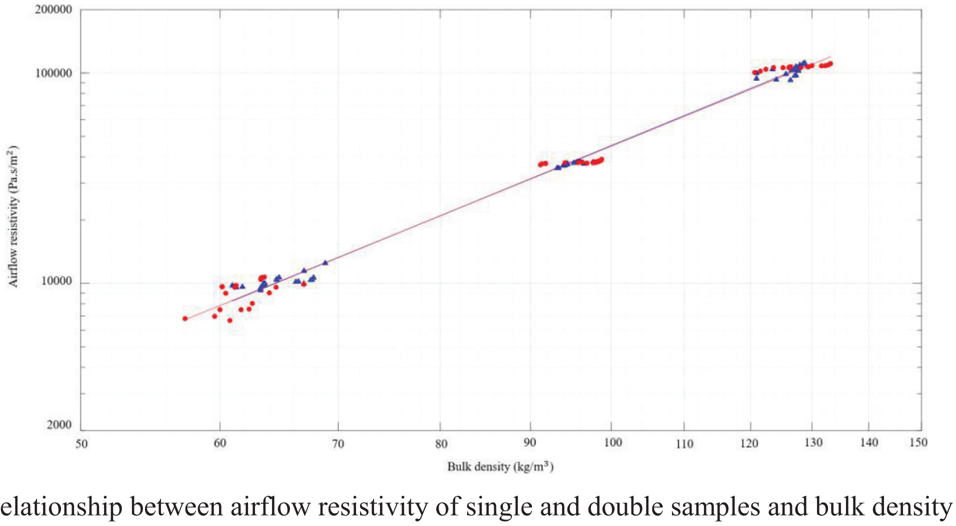

Figure 2 - Relationship between airflow resistivity of single and double samples and bulk density at room temperature: Regression plots for the ISO test rig (blue) and the high temperature test rig (red).

3.2 High temperature measurements

All the high temperature measurements used double samples to ensure a measurable differential pressure. During initial experiments it was observed that the measured thickness of the material was different before and after exposure to high temperatures. According to (6), AES is almost amorphous at room temperature but undergoes crystallization and shrinkage near 900°C although the properties start to change between 750 and 800°C. When there is an unknown reduction in thickness at high temperature it is not possible to calculate the airflow resistivity as this requires knowledge of the thickness. Therefore it is more appropriate to calculate the specific airflow resistance to assess changes over a wide range of temperatures. In addition this reduction in thickness means that it is no longer possible to attribute a bulk density to the material above 600°C such that regression analysis needs to use sample mass rather than density.

3.2.1 Regression analysis to relate specific airflow resistance to sample mass for different density materials

Empirical relationships are sought using the mass of each double sample at different temperatures. The regression lines are plotted along with the individual data points in Figure 3 confirming that the specific airflow resistance depends on the mass of the sample. Up to 600°C, the gradient of the regression lines is similar but it changes significantly at 700°C and 800°C as crystallization occurs.

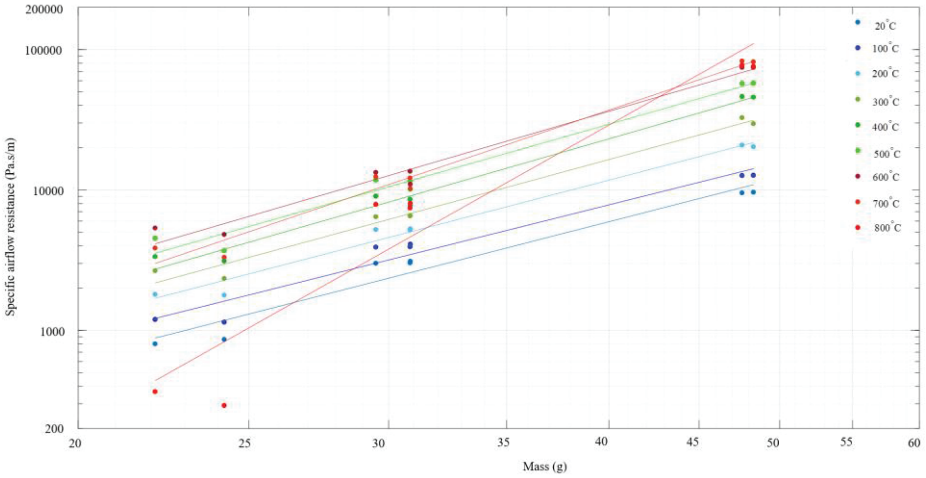

Figure 3 - Relationship between specific airflow resistance and mass of the double samples at temperatures between 20 and 800°C.

3.2.2 Power law relationship between airflow resistance and temperature

From the Poiseuille law, airflow resistance is proportional to air viscosity and Sutherland (8) has shown that the viscosity for ideal gases is proportional to T^n where the exponent n ranged from 0.7 for hydrogen to 1.0 for other gases. Hence, when relationships are sought between the airflow resistance and temperature it is reasonable to assume that airflow resistance will be proportional to T^n because airflow resistance is proportional to air viscosity.

From experimental work, Christie (3) stated that air viscosity varied with $T^{0.7}$ and whilst Christie did not prove this it can be shown to be a reasonable estimate by using regression analysis of data calculated with Sutherland's equation (8). For rock wool at temperatures up to 400°C, Christie's measurements indicated that airflow resistance was proportional to $T^{0.6}$. However, Miglietta et al (10) concluded that it varied with $T^{1.2}$ based on measurements between 0 and 30°C on a range of materials (including generic materials such as polyethylene, rubber, glass wool, rock wool, cotton waste, and polyester).In order to identify the power law relationship between specific airflow resistance and temperature for AES material, regression analysis was carried out from 20 to 600°C (higher temperatures were not considered because the material changed significantly above 600°C). Power law regression for each material density gave a close fit to the measured data (coefficient of determination $R^2>0.99$). However, the average exponent n was 1.6 which is larger than those published in the literature mentioned above; hence it would be worthwhile testing different materials in future projects to see whether similarly high values occur with other materials.

4. CONCLUSIONS

A "high temperature" test rig has been designed for measurements of airflow resistance at temperatures up to 800°C by modifying a design used by Christie (3). This has allowed measurements on Alkaline Earth Silicate (AES) fibrous materials of three different densities. A room temperature comparison was made of the high temperature test rig and an "ISO" test rig built according to ISO 9053-1:2018. These measurements were carried out using single samples and double samples (i.e. two samples on top of each other) because it was expected that double samples would eventually be needed to achieve measurable differential pressure drops at high temperatures. The statistical tests were more reliable for the combination of single and double samples and confirmed that there was no significant difference between the two test rigs.

High temperature experiments were conducted up to 800°C using double samples to ensure a measureable differential pressure. However, after exposure to temperatures above 600°C the thickness of the AES material decreased due to crystallization and due to the opaque test rig this decrease in thickness could not be quantified at individual temperatures; hence all measurements reported the specific airflow resistance rather than airflow resistivity. The high temperature tests on AES materials indicated that it might be possible to assume no significant effect of temperature on specific airflow resistance between 20 and 100 °C but not at higher temperatures. The specific airflow resistance depends on the mass of the sample up to 800°C. Up to 600°C, the dependence is similar but as the AES material crystallizes at 700°C and 800°C it changes significantly.

Regression analysis was also used to establish that the specific airflow resistance is proportional $T^{1.6}$ for this AES material.

In this paper the measurements were all carried out using an airflow velocity of 0.5×10^{-3} m/s. However, additional measurements (not reported in this paper) show that at room temperature there is little change in the specific airflow resistance when measured with flow velocities between 0.5×10^{-3} and 4×10^{-3} m/s but there can be significant differences at 800°C. Hence for high temperature applications the airflow velocity will need to be chosen to correspond to the sound pressure level for the specific industrial application.

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