**Airflow resistance measurement of fibrous materials at high temperatures for acoustical applications**

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Keywords: airflow resistance; porous; fibrous; high temperature

**Abstract**

For some industrial applications it is necessary to assess the acoustic properties of porous materials at high temperatures; hence, airflow resistance measurements on fibrous materials have been carried out at temperatures up to 800℃. A comparison of a high temperature test rig and a test rig satisfying the requirements of ISO 9053-1 indicated no significant difference between the two rigs at room temperature. For measurements in the high temperature test rig at and above 600℃ there were changes in the sample thickness that could be linked to the onset of crystallisation. This meant that regression analysis had to establish relationships between the sample mass (rather than bulk density) and the specific airflow resistance (rather than airflow resistivity). Power law regression for AES, basalt wool and rock wool show that, on average, the specific airflow resistance is proportional to *T*0.7 (where *T* is the absolute temperature in Kelvin) at temperatures where there has been no reduction in sample thickness or other material change due to temperature. For fibrous materials, these results provide more evidence that the temperature-dependence is mainly determined by the air viscosity. Measurements on AES at 20℃ indicate negligible change in the specific airflow resistance when measured with flow velocities between 0.5×10‑3 and 1.83×10-3 m/s but significant differences at 800℃.

**1. Introduction**

Sound absorption by, and sound propagation through porous materials is partly described by their ability to resist airflow as quantified by their airflow resistance. For different types of porous materials, empirical relationships can be established between airflow resistance and bulk density (e.g. see [[[1]](#endnote-1),[[2]](#endnote-2),[[3]](#endnote-3)]). For materials with a rigid skeletal frame and porosities close to unity, sound propagation can be modelled with a single longitudinal wave by using the concept of an equivalent gas to represent the porous material and the gas (usually air) that is contained within it [[[4]](#endnote-4)]. The concept of an equivalent gas allows sound propagation in porous materials to be described using two parameters, the complex wavenumber and the characteristic impedance. These parameters can be calculated from the effective density and the effective gas compressibility when the structure of the porous material is known, or can be represented using idealized geometry. Delany and Bazley [[[5]](#endnote-5)] developed a simpler approach and established empirical relationships that related the complex wavenumber and the characteristic impedance to the measured airflow resistivity. These relationships were refined in later years to improve the low-frequency estimates (e.g. see [[[6]](#endnote-6)]) along with more complex models that require additional measured properties (e.g. see [[[7]](#endnote-7)]). This led to airflow resistivity measurements being widely used to characterise porous materials at room temperature to assess sound absorption in buildings. In comparison, much less work has been carried out on quantifying the acoustic performance of fibrous materials at temperatures that are much higher than room temperature. However, measurements on basalt wool show that the sound absorption decreases with increasing temperature up to 500℃ [[[8]](#endnote-8)]. Hence there is an incentive to be able to quantify acoustic performance for industries with high temperature applications such as gas turbine exhaust silencers in a Heat Recovery Steam Generator (HRSG), aero engine liners, combustion chambers, and automotive silencers. The motivation in this paper relates to the use of Alkaline Earth Silicate (AES) fibrous material in HRSG applications. This material is used to reduce sound levels inside the silencers and near the exhaust area which can operate at temperatures between 800 and 1300℃.

Empirical relationships for the airflow resistivity of fibrous materials at room temperature show a dependence on air viscosity, porosity, air density and fibre diameter (e.g. see [2]). Increasing the temperature will increase the air viscosity (e.g. see [[[9]](#endnote-9)]), and if other factors remain relatively unchanged, this will increase the airflow resistivity. However, the fibrous frame will change with increasing temperature. The fibre diameter depends on the thermal expansion coefficient of the material, which, in turn, changes the fibre density and the porosity. The porosity is also determined by the bulk density which could potentially change if any binder (that holds the fibres together) evaporates. As the temperature increases and the material crystallises as it gets closer to the melting point, the skeletal fibrous frame can be expected to change, potentially affecting the pore shape and tortuosity. At room temperature, laboratory measurements of airflow resistivity, sound absorption and impedance for fibrous materials are common and this has led to empirical datasets (e.g. see [2,5]) alongside a range of validated prediction models (e.g. see [7]); however, much less information is available for high temperatures.

Early work on high temperature measurements was carried out by Christie [[[10]](#endnote-10)] on starch-bonded mineral wool (Stillite SR5, 80 kg/m3) for which the airflow resistivity was measured from 19 to 600℃ and the acoustic impedance was measured at 19, 255 and 490℃. For the airflow resistivity measurements, Christie used flow velocities in the range 1×10-2 to 4×10-2 m/s and found no significant change in the resulting airflow resistivity. Inserting the measured airflow resistivity into the empirical equations of Delany and Bazley allowed Christie to predict the complex wavenumber and the characteristic impedance to within 20% of measured values. This indicated the potential merit in measuring airflow resistivity at high temperatures which is simpler, cheaper and quicker than carrying out impedance tube measurements at high temperatures. Christie observed that the airflow resistivity was proportional to *T*0.6 where *T* is the absolute temperature in Kelvin. However, this exponent of 0.6 appears to have been calculated using data between room temperature and 400℃ because the airflow resistivity reached a plateau above 400℃ with a slight reduction at 600℃. This indicates that the mineral wool might have undergone a physical change at the highest temperatures, although this was not mentioned, and no analysis was carried out to assess this. Miglietta et al [[[11]](#endnote-11)] carried out airflow resistivity measurements between 0℃ and 30℃ on a range of materials (including polyethylene, rubber, glass wool, rock wool, cotton waste and polyester) and showed that the airflow resistivity varied with *T*1.2. As the upper temperature was only 30℃ it is unlikely that there were significant effects due to physical changes to the materials under test. Sun et al [[[12]](#endnote-12)] experimentally validated a prediction model for the sound absorption of fibrous metal materials using an impedance tube up to 500°C for which the general trend was a reduction in the sound absorption with increasing temperature. Williams et al [8] also used a standard impedance tube up to 500°C on rock, glass and basalt wool. This provided some evidence to support Christie’s finding that airflow resistivity was proportional to *T*0.6 and that it was possible to determine temperature-dependent Delaney and Bazley parameters up to 500°C using impedance tube measurements at room temperature with a modified airflow resistivity that accounts for temperature dependency. However, the universal applicability of *T*0.6 is questionable in the light of the *T*1.2 relationship identified by Miglietta et al. In previous studies that used an impedance tube, a temperature limit of approximately 500°C has primarily been set by the difficulty in achieving thermal isolation and cooling for the microphone(s) and loudspeaker. Hence for industrial applications above 500°C there is a potential benefit in using simpler, cheaper measurement equipment for airflow resistivity rather than needing an impedance tube.

The aim in this paper is to extend the temperature for the measurement of airflow resistance of fibrous materials up to 800°C which is more relevant to its use in some industries. This is carried out using a high temperature test rig based on a design developed by Christie [10]. Before carrying out the high temperature tests, a test rig commonly used for room temperature measurements of airflow resistance described in ISO 9053-1 [[[13]](#endnote-13)] is compared with the high temperature test rig when at room temperature (20℃) to check that it gives nominally identical results. The high temperature test rig is then used to establish and assess empirical relationships between airflow resistance and the mass of the sample, and airflow resistance and temperature.

**2. Experimental work**

**2.1 Definitions used to quantify airflow resistance**

For a specific thickness of porous material, the specific airflow resistance, *R*S, (Pa.s/m) is defined as

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|  | (1) |

where Δ*P* is the differential pressure (Pa) across the porous material when air is flowing through the sample at a linear airflow velocity, *u* (m/s).

For homogeneous, porous materials of known thickness, *d*, the airflow resistivity, *r*, (Pa.s/m2) can be quoted which is calculated as follows:

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| --- | --- |
|  | (2) |

**2.2 Room temperature test rig**

The test rig for room temperature measurements was designed to satisfy the requirements of ISO 9053‑1 [13] and ASTM C522 [[[14]](#endnote-14)] using the direct airflow method with controlled unidirectional airflow through the test specimen – see Figure 1. In order to visually check the position of the test sample, clear 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 air underneath the sample and atmospheric pressure.

**2.3 High temperature test rig**

The high temperature test rig was based on the design of Christie [10] but with the aim of extending its use above 500℃. The rig has a cylindrical cross-section (internal diameter of 100 mm) and consists of a preheating chamber (259 mm height) and a specimen holder (198 mm height) – see Figure 2. The preheating chamber consists of an air inlet, a tap for the differential pressure probe and one tapping point for a thermocouple to measure the air temperature of the air leaving the preheating chamber and entering the test sample. The specimen holder has a perforated mesh to hold the sample in place, a tap for the differential pressure probe above the specimen and an air outlet at the top.

The initial aim was to design a test rig to withstand temperatures up to 1000℃; hence it was necessary to check whether the length of the preheating chamber needed to be longer than that used by Christie [10] to ensure that the supply air arriving at the test sample reached the same temperature as the air in the kiln. This process was modelled using Matlab Simulink software to identify a suitable length for the preheating chamber that would achieve the required temperature in the chamber where the air enters the test sample. It was assumed that heat transfer occurs from the kiln to the preheating chamber due to convection and conduction, ignoring the radiation from the surfaces of the kiln. It was not possible to accurately simulate a fibrous packing material in the preheater simulation; hence the worst case scenario of an empty preheater was used to identify that a suitable length for the preheater was 250 mm. This was adopted to ensure that the air was heated to the correct temperature before it entered the sample.

To fabricate the test rig, Grade 310 austenitic stainless steel was initially selected through consideration of the material strength and corrosion resistance. However, due to the lack of availability of hollow tubes of Grade 310 austenitic stainless steel at the time, and potential difficulty in machining it, Grade 316 was used instead. The maximum temperature that was feasible for measurements with Grade 316 was expected to be approximately 900℃. Therefore, in order to assess the thermal stability and the thermal stress at 900℃, finite element analysis was carried out for the high temperature test rig design using Autodesk Mechanical Simulation software. Thermal stress was simulated by coupling transient heat transfer and structural analysis. This showed that the rig design with Grade 316 austenitic stainless steel would fail at temperatures near 900℃, particularly near the connection points on the specimen holder cap; hence the upper temperature for all measurements with the high temperature test rig was reduced to 800℃. For future work where cost is not a prohibitive factor, the test rig could be made of quartz to provide a transparent specimen holder which could withstand temperatures above 1000℃.

The preheater contains a packing material so that the air enters the sample at the same temperature as the internal kiln temperature and there is uniform airflow across the surface of the sample. After performing several experiments with different packing materials, the material chosen was 50 mm AES (Morgan Superwool® Plus Blanket) as it has a high melting point (above 1093℃), 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 needed pressure taps on the sample holder to determine the differential pressure across the sample.

The high temperature test rig is installed inside a front-loading kiln (see Figure 3) that was rated for a maximum temperature of 1100℃. To provide a uniform distribution of heat inside the kiln, the heavy-duty heating elements were positioned on three sides. The temperature ramp rate for the kiln was set to 100℃ per hour and the internal air temperature was measured using a K-type thermocouple and a digital thermometer (Tenma 72-10390A).

**2.4 Airflow velocity**

Airflow resistance measurements according to ISO 9053-1 and ASTM C522 require a minimum airflow velocity of 0.5×10-3 m/s which could be controlled to ± 0.01×10-3m/s using the valve. As the cross-section of the sample holders are all 100 mm diameter, this gave a range of volumetric flow rates between 0.231 and 0.240 l/min.

For the application of sound absorption inside buildings, using an airflow velocity of 0.5×10-3 m/s makes a link to a sound pressure level of 80.3 dB (re 2×10‑5 Pa) in a plane wave at 20℃ [[[15]](#endnote-15)]. This is a practical choice as noise control tends to be required at this level to avoid adverse effects for human exposure to noise. In addition, the airflow should remain laminar, and not become turbulent. Hence whilst the noise levels inside industrial plant tend to be significantly higher it is not feasible to significantly increase the airflow velocity to represent higher sound pressure levels. However, the opportunity was taken to assess the effect of higher airflow velocities (up to 1.83×10-3 m/s) on the measured airflow resistance at 20℃ (room temperature) and at 800℃.

**2.5 Measurement equipment**

A single instrument (Furness Controls FCS 523) is used to measure differential pressure and airflow rate; this consists of two main parts, a laminar flow meter and differential pressure meter. This instrument is designed to be used at room temperature but is able to withstand a maximum temperature of 34℃. Fortunately, pre-tests showed that the air temperature at the instrument was close to room temperature; hence, there was no need to use a heat exchanger on the connecting pipework.

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 was necessary to reduce the supply air pressure (1200 kPa) and to dehumidify the supply air before it enters the meter. This was achieved with a pressure regulator and air filter. The air temperature from the compressed air supply was 17°C.

From the ideal gas equation, pressure is proportional to absolute temperature. Hence to calculate the specific airflow resistance (Eq. (1)) or airflow resistivity (Eq.(2)) with the high temperature test rig it was necessary to convert the differential pressure that was measured outside the kiln at room temperature to the differential pressure that would exist inside the test rig at high temperature using:

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|  | (3) |

where *P*1′ and *P*2′ indicate the actual pressure on either side of the sample inside the test rig at temperature, *T*'′ in Kelvin, and *P*\* indicates the pressure that was measured by the equipment outside the kiln for air at room temperature, *T*'\* in Kelvin.

The laminar flow meter 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. The device generates a very low differential pressure, while offering little restriction to the flow, typically a pressure drop of 100 Pa at a full flow rate of 2 l/min. The flow was measured at the inlet and a correction was made to calculate the airflow velocity inside the kiln which was above room temperature using

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| --- | --- |
|  | (4) |

where the linear airflow velocities in Kelvin are *u*′ inside the high temperature test rig and *u*\* entering the laminar flow meter from the compressed air supply.

**2.6 Test samples**

Three different fibrous materials were used: AES, basalt wool and rock wool. Bulk densities were 64, 96 and 128 kg/m3 for AES (nominal thickness of 50 mm), 85 and 115 kg/m3 for basalt wool (nominal thickness of 50 mm) and 80 and 100 kg/m3 for rock wool (nominal thickness of 100 mm). Different densities were used to investigate the relationship between airflow resistance and bulk density over a range of temperatures.

From Eq. (3) the differential pressure at high temperature is lower than at room temperature; hence it was expected that to achieve a measurable differential pressure with AES and basalt wool, two samples would need to be stacked on top of each other to give a nominally 100 mm thick sample (i.e. to form a ‘double sample’). Hence all measurements in the kiln with the high temperature test rig between 20 and 800℃ were carried out with material that had an overall thickness of 100 mm.

AES was used to compare the test rig satisfying the requirements of ISO 9053-1 with the high temperature test rig when both were at room temperature. This material spanned a wide range of bulk density which allowed an assessment of the different test sample holders in the two test rigs for which ‘soft’ (low density) and ‘stiff’ (high density) samples might be fitted differently. A potential difference was that the ISO rig was transparent so that the fitted sample could be seen from the side. This was not possible with the high temperature rig that was made of steel. However, to ensure that the sample in the high temperature rig was fitted to the correct depth, grooves were etched on the inside so that it was possible to check that the upper surface of the sample was in the correct position.

**3. Results and analysis**

**3.1 Comparison of the ISO and high temperature test rigs at room temperature**

The ISO and the high temperature test rigs are both used to carry out room temperature (20℃) measurements to check that they give nominally identical results with an airflow velocity of 0.5×10-3 m/s. This used single and double samples of the three different densities of AES material. The measured thickness of the samples when installed inside the test rigs and the measured mass is used to calculate the bulk density and to calculate results in terms of the airflow resistivity.

Table 1 shows the average results from ten single samples and ten double samples of each AES material density at room temperature indicating the increase in airflow resistivity with increasing density. The coefficient of variation (CoV) is highest for the low-density material which is potentially attributed 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, analysis of variance (ANOVA) tests indicate significant differences (*p*≤0.05) for the 64 and 96 kg/m3 materials and non-significant differences (*p*>0.05) for the 128 kg/m3 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 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. A 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*≤0.05) between single and double samples. This is attributed to the different fitting of the samples inside the test rigs.

Linear relationships between airflow resistivity and bulk density were established by taking the logarithm of both parameters as carried out by Nichols [1]. Regression curves were determined from the two test rigs using the three material densities and single and double samples as shown in Figure 4. One-way ANOVA for the two regression models showed that there is a statistically non-significant difference (*p*>0.05) between the intercepts and gradients for the two different types of rigs. Therefore, it is concluded that the measured airflow resistivity at room temperature does not differ between the two test rigs.

**3.2 High temperature measurements**

For the high temperature measurements, two different densities of AES, basalt wool and rock wool were tested. For the AES and basalt wool, measurements were carried out on two double samples (i.e. 2×50 mm thickness) of each density. For the rock wool, two 100 mm samples of each density were tested. For all tests, the airflow velocity inside the high temperature test rig was estimated to be 0.5×10-3 m/s using Eq. (4); this required adjusting the airflow with the regulator for each temperature setting.

During pre-tests it was observed that the measured thickness of the AES material was different before and after exposure to 800℃ by up to 18%. However, there was no measurable change in thickness up to 600℃. X-ray diffraction (XRD) was carried out on all the fibrous materials after heating to 800℃ using the same ramp rate as in the airflow measurements to assess whether the onset of crystallisation had occurred. This onset causes densification of the material accompanied by a reduction in thickness and is evident at 800℃ for AES, basalt wool and rock wool. With the rock wool the binder evaporates near 250℃ but the material tends to retain its cohesiveness above this temperature [[[16]](#endnote-16)] and the results in this paper do not show any step change when this evaporation occurs.

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℃; hence regression analysis needs to use sample mass rather than density. This meant that at each temperature, a linear empirical relationship was sought between the mass of each double sample and the specific airflow resistance. A potential improvement to the high temperature test rig would be to embed sensors that could monitor the change in sample thickness inside the specimen holder.

**3.2.1 Regression analysis to relate specific airflow resistance to sample mass**

Relationships between the mass of each double sample and the specific airflow resistance at temperatures between 20 and 800°C are shown in Figure 5 with regression lines at each temperature.

For AES, basalt wool and rock wool, the regression lines tend to align in a monotonically increasing sequence with increasing temperature up to 500 or 600℃. However, this changes at 700 and 800℃ as the materials begin to crystallize. For all three materials this is particularly evident at 800℃ where the specific airflow resistance is significantly reduced. This has implications for the calculation of power law relationships in the following section.

**3.2.2 Power law relationship between airflow resistance and temperature**

From the Poiseuille law, airflow resistance is proportional to air viscosity. Sutherland [9] has previously 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 a reasonable starting point to assume that airflow resistance will be proportional to *Tn* because airflow resistance is proportional to air viscosity. However, for a fibrous material there will be other properties such as porosity and fibre diameter that will also change with increasing temperature and these will also affect the airflow resistance.

Christie [10] stated that the viscosity of air varied with *T*0.7 but this was not proven. However, it is possible to prove this by using Sutherland’s equation as this is valid for air at temperatures from –173℃ to 1627℃ (i.e. 100 K to 1900 K) [[[17]](#endnote-17)] and is given by [[[18]](#endnote-18)]

|  |  |
| --- | --- |
|  | (5) |

where *η* is the viscosity (kg/(m.s)) and *η*0 corresponds to the viscosity at absolute temperature *T*0. For *T*0=300 K and *η*0=1.846×10‑5 kg/(m.s), the constant *T*S=110 K.

Using Eq. (5) the viscosity of air can be plotted against a range of absolute temperatures from 293 K (room temperature) up to 873 K as shown in Figure 6. Power law regression is then used to identify the exponent which indicates that the air viscosity varies with *T*0.68. This exponent, 0.68, can be rounded to one decimal place to give the exponent value of 0.7 that was quoted by Christie [10].

To identify a power law relationship between specific airflow resistance and temperature, regression analysis was carried out using the average specific airflow resistance of the two double samples. The temperature range used for this regression was between 20℃ and an upper temperature that depended on the type of material. The upper temperature was the highest temperature at which the specific airflow resistance was still increasing monotonically; this was 500 or 600℃ for AES, and 700℃ for basalt wool and rock wool. The power law relationships are shown in Figure 7 for which the regression lines have a close fit to the measured data (coefficient of determination, *R*2>0.89).

For AES, basalt wool and rock wool, the average exponent from the two different densities is 0.8, 0.6 and 0.8 respectively, which gives an overall average for the exponent of 0.7. This corresponds to the exponent derived from the temperature-dependent air viscosity. It is also close to the value of 0.6 from Christie’s measurement on one type of rock wool up to 490℃. However, it is significantly different to the value of 1.2 quoted by Miglietta et al [11] for a range of materials over a much narrower temperature range from 0 up to 30℃. Although the exponents for these three fibrous materials are similar, it is not known whether the thermal expansion coefficients are similar; hence caution should be exercised before assuming that these exponents are indicative of other fibrous materials. However, the results indicate that the exponent is primarily determined by the change in air viscosity with temperature as suggested by Christie [10] and that any changes to the fibrous frame did not significantly affect the airflow resistance. These measurements indicate that any future work to establish high temperature relationships between airflow resistance and temperature needs to assess the temperature at which the material properties and thickness can change, particularly near the onset of crystallisation for fibrous materials.

**3.3 Effect of airflow velocity at room temperature and 800°C**

For double samples of AES material, specific airflow resistance measurements were carried out using nine different airflow velocities between 0.5×10-3 and 1.83×10-3 m/s. The individual results at 20°C and 800°C are shown in Figure 8 alongside straight line regression to illustrate the trends. At 20°C there is no significant difference between the specific airflow resistance values at the different airflow velocities. However, at 800°C there is a significant increase in the specific airflow resistance with airflow velocity for the low mass samples. For this reason, it is critical that high temperature measurements are carried out using 0.5×10-3 m/s (potentially lower might be preferable) for low density fibrous materials as the increase in airflow resistance with airflow velocity implies that an assessment of the acoustic properties could be in error. Christie [10] did not find a significant change in the airflow resistance with increasing airflow velocity and this could be due to the use of velocities that were an order of magnitude higher than were used in the current paper.

**4. Conclusions**

A high temperature test rig has been used to measure the airflow resistance of fibrous materials at temperatures up to 800℃. A comparison of the high temperature test rig and a test rig satisfying the requirements of ISO 9053-1 was carried out at room temperature using three different densities of AES fibrous material. This confirmed that there was no significant difference in the airflow resistivity from the two test rigs.

X-ray diffraction indicated that the onset of crystallisation was evident at 800℃ for AES, basalt wool and rock wool. However, even at 600℃ for AES there was evidence of a reduction in thickness and densification which could be attributed to this onset. Uncertainty in the actual thickness of the sample at high temperatures meant that the measurements were reported in terms of the specific airflow resistance, whereas airflow resistivity is more commonly used for fibrous materials at room temperature. For this reason, regression analysis was used to establish relationships between the sample mass (rather than bulk density) and the specific airflow resistance (rather than airflow resistivity) at different temperatures. However, the specific airflow resistance did not follow a monotonic increase with increasing temperature above 600℃ for all three materials.

Sutherland’s equation has been used to demonstrate that air viscosity, and hence airflow resistance is proportional to *T*0.7 as indicated by Christie [10]. Power law regression for AES, basalt wool and rock wool showed that, on average, the specific airflow resistance is proportional to *T*0.7 at temperatures where there has been no reduction in sample thickness or densification near the onset of crystallisation. This provides more evidence that the temperature-dependence is mainly determined by the air viscosity

At room temperature there was negligible change in the specific airflow resistance of AES when measured with flow velocities between 0.5×10-3 and 1.83×10-3 m/s but there were significant differences at 800℃. Hence for high temperature applications it is necessary to check that the airflow velocity is sufficiently low that there is no effect on the measured airflow resistance.

As industrial applications require absorption at temperatures above 600℃, future work could investigate how physical changes to the fibrous materials at high temperatures cause a reduction in the airflow resistance and how their sound absorption can be predicted when relatively thin sheets are combined to make a thick layer that (due to its thermal insulating properties) will have a strong temperature gradient across it.

**Acknowledgement**

The authors are very grateful for the funding provided by Morgan Advanced Materials Plc.

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Figure 1. ISO test rig.



Figure 2. High temperature test rig.



Figure 3. High temperature test rig inside the kiln with the experimental apparatus.



Figure 4. Relationship between airflow resistivity and bulk density at room temperature for the combination of single and double samples for AES material. Data points and regression lines for the ISO test rig are shown with blue triangles and for the high temperature test rig with red circles.



Figure 5. Relationship between specific airflow resistance and mass of the double samples at temperatures between 20 and 800°C for (a) AES material, (b) basalt wool and (c) rock wool. The plots show the individual data points at each temperature and their regression lines.



Figure 6. Relationship between the viscosity of air and absolute temperature using data calculated with Sutherland’s equation.



Figure 7. Relationship between specific airflow resistance and absolute temperature for different densities of AES, basalt wool and rock wool.



Figure 8. Specific airflow resistance of AES material for different airflow velocities at 20°C (upper) and 800℃ (lower) with regression lines.

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

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| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| Single or double samples | Bulk density (kg/m3) | ISO test rig | | | | High temperature test rig | | | |
| Average thickness  (mm) | Average airflow resistivity  (Pa.s/m2) | Standard  deviation  (Pa.s/m2) | CoV  (-) | Average thickness  (mm) | Average airflow resistivity  (Pa.s/m2) | Standard  deviation  (Pa.s/m2) | 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 |

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