INFLUENCE OF FIBER DIAMETER MEASUREMENT TECHNIQUES ON AIRFLOW RESISTIVITY PREDICTED BY THE BIES–HANSEN MODEL

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Abstract

In acoustics, the Bies-Hansen model is a well-established empirical correlation for estimating the airflow resistivity (AFR), supporting the design and evaluation of fibrous acoustic materials such as mineral wool. It provides a mathematical relationship between the physical properties of material—including bulk density and fiber diameter—to AFR. The model's empirical constants were originally derived for fiberglass materials with negligible binder content, under the assumption of uniform fiber diameters below 15 µm. In the original correlation, fiber diameter was represented by a mean value used to fit the constants. In practice, multiple techniques are available for fiber diameter determination, each based on different measurement principles and data interpretation. Moreover, it is questionable if the mean value fully captures the complexity of non-uniform fiber diameter distribution typical for fibrous materials.

This study compares several fiber diameter measurement approaches and assesses the agreement between measured AFR and Bies–Hansen predictions when each measurement method's diameter is used in the model. It outlines how measurement technique selection affects the derived fiber diameter and therefore the predicted AFR. The study highlights that variations in fiber diameter determination methods affect AFR predictions and underscores the need to recalculate the original empirical constants for better alignment with measured values. Recalibration improves model fidelity across materials with different properties and non-uniform diameters, enabling more reliable AFR prediction beyond the original scope of the Bies–Hansen correlation.

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1. Introduction

Airflow resistivity is a key parameter in the evaluation of the acoustic performance of fibrous materials and is widely used to characterize porous absorbers. It is particularly important in the noise reduction applications, as it describes the resistance to airflow through the material. More precisely, airflow resistivity is defined as the ratio of the pressure drop across a sample layer to the resulting airflow velocity. [1, 2]

Several models relate airflow resistivity to the acoustic behavior of fibrous materials through parameters such as bulk density and fiber diameter [2]. In this study, the well-established empirical Bies-Hansen model was used to investigate the relationship between these properties. The aim was to assess how accurately the model can be used to estimate airflow resistivity from fiber diameter and material density, and to compare these predictors with results obtained from direct airflow resistivity measurement. [1, 2]

The Bies-Hansen model provides a mathematical relationship between the physical properties of the material, such as density, fiber diameter, and its airflow resistivity:

$$\sigma d^2 \rho_m^{-K_1} = K_2 \qquad (1)$$

where σ is the airflow resistivity [Pa s/m^2], ρ_m is the bulk density of the fibrous material [kg/m^3], d is the fiber diameter [m], and both K_1 and K_2 are dimensionless empirical constants, where K_1 corresponds to 1.53 and K_2 to $3.18 \cdot 10^{-9}$. The empirical constants were derived for fiber glass materials, where Bies and Hansen assumed that the material has a uniform fiber diameter, which is less than 15 µm, and

that there is negligible binder content in the sample. The K_2 value was determined at fiber density $\rho_f = 2.5 \cdot 10^3$ kg/m³ and the viscosity of air $\mu = 1.84 \cdot 10^{-5}$ Poiseuille at standard conditions [1]. In this study the airflow resistivity was measured by the Airflow Resistivity Meter AED 300 - AcousticFlow®. The AcousticFlow® is a tool used for determining airflow resistance, the specific airflow resistance, the effective specific airflow resistance, and the airflow resistivity of specimens in the laboratory or in situ.
Fiber diameter can be determined using a range of measurement techniques, each based on distinct measurement principles and data interpretation approaches. This study focused on three methods: Micronaire, Diamscope, and scanning electron microscopy.

Micronaire is an airflow instrument originally developed in the 1940s for the wool industry to provide faster and more repeatable measurements. It is also widely used in the cotton industry as a standard characterization method. The principle of the measurement is based on the pressure drop generated when air is forced through a fiber mat of known mass. A defined mass of fibers is placed in a chamber where air is forced through the material, and the resulting resistance to airflow is measured and calibrated to estimate the fiber diameter. The result is reported as a single value representing the average fiber diameter, without information on the diameter distribution, fiber length, or the number of fibers measured. The reliability of the diameter estimate depends strongly on the quality and suitability of the calibration.

The Diamscope is an optical instrument designed for the direct measurement of fiber diameters and lengths of individual fiber segments. It enables a comprehensive analysis of fiber diameter distribution and provides rapid results. The image analysis algorithm measures fiber diameter to a fraction of a pixel and applies pattern recognition techniques. Measurements are performed in a water-filled cell, where a digital camera captures 50 images per second and each image is analyzed in real time. As with any optical method, the measured diameter may be influenced by fiber opacity, ellipticity, and the wavelength of light. In addition, the optical resolution is limited by the LED light source, resulting in a shallower depth of focus than that achieved with electron microscopy.

Scanning electron microscopy is a highly advanced method of measuring fiber diameter by using electron beams to generate high-resolution images of the fibers. Its superior resolution and depth of focus make it the most reliable method for capturing detailed fiber characteristics. The method is not limited by light wavelengths, avoiding the resolution constraints of optical methods. Fibers must be evenly dispersed on a sample stub and are prior to the imaging coated with gold or carbon to prevent charging issues. Scanning electron microscopy (SEM) also reveals additional features such as surface roughness, shape irregularities, and defects. These characteristics may influence airflow resistance, but they are not captured by other techniques.

2. Materials and methods

2.1 Mineral fibers

In this study, 10 different glass mineral wool products were used with thickness ranging from 45 to 200 mm, and density from 13 to 32 kg/m³. The samples were produced under different process parameters.

2.2 Airflow resistivity

Airflow resistance was determined on the basis of the static-airflow method described in ISO 9053-1:2018: "Acoustics - Determination of airflow resistance – Part 1: Static airflow method", with an Airflow Resistivity Meter. The technique requires the measurement of the pressure drop across the specimen to be examined as a function of the volume airflow. It allows the investigation of the materials with open porosity. During the measurement, specimen of specified mass and size is placed inside measurement tube, where it is exposed to air pressure. [3]

2.3 Fiber diameter determination techniques

2.3.1 Micronaire

Prior to testing, the device was calibrated using a calibration plug at 4.5 psig. The Micronaire output, referred to as the Micronaire reading, represents the fiber diameter calculated from the pressure drop of airflow through the fiber sample. For each measurement, 4.5 g of material was used.

2.3.2 Diamscope

Samples were first ignited in a furnace for 30 minutes at 550 °C and, after ignition, were shortened into smaller fragments using a guillotine cutter. The shortened fibers were then dispersed in distilled water in the Diamscope bowl using a magnetic stirrer. A minimum of five replicates was measured for each sample, with at least 3000 fibers analyzed in each measurement replicate. Fresh fibers were used for each replicate. The lower measurement limits were set to 0.1 µm for fiber diameter and 0.1 mm for fiber length.

2.3.3 Scanning electron microscopy

Fiber diameters and lengths were measured using a Phenom ProX Desktop SEM (Thermo Scientific). Samples were first ignited in a furnace at 550 °C for 30 minutes and then shortened by sieving through a 63 µm sieve. The shortened fibers were dispersed in ethanol and applied onto a 12 mm sample stub. Prior to imaging, the samples were sputter-coated with gold. For each sample, a minimum of two replicates was prepared, and two areas per stub were imaged. To ensure statistical relevance, at least 1000 fibers were measured. The images were analyzed using Image-Pro 11.3 (Media Cybernetics), employing an automated separation protocol to distinguish crossing fibers and measure both the diameter at the midpoint and the length of individual fiber segments.

2.4 Description of different distributions

While Bies-Hansen model assumes a uniform fiber diameter distribution, the latter is more complex in fibrous materials. The fiber diameter distribution in mineral wool can be described in several ways. It is often assumed to be log-normal, although depending on the process parameters it may also be normal, bimodal, multimodal, or follow another distribution. Correct description of the fiber diameter distribution is important when selecting the most appropriate mean diameter, since the methods used in this study are based on different measurement principles and yield different statistically derived diameter values.

Results obtained from the Diamscope, and SEM are usually presented as length-weighted fiber diameter measures. In this approach, longer fibers contribute more to the final average than shorter fibers. If all fibers had the same length, a length-weighted measure, such as the length-weighted arithmetic mean, would be identical to the simple arithmetic mean fiber diameter.

In this study fiber diameter was described using the following statistical measures:

- Median fiber diameter: the midpoint of the diameter distribution, at which 50% of the measured diameters are below this value and 50% are above it,
- Arithmetic mean diameter (AMD): the average diameter, typically used when the fiber diameter distribution is assumed to be normal (Gaussian),
- Geometric mean diameter (GMD): a measure better suited to strongly skewed distributions, particularly log-normal distributions, and therefore often more appropriate when the fiber diameter distribution is closer to log-normal than to normal.

Statistical analysis was performed using JMP 18 (SAS Institute).

3. Results

3.1 Fiber diameter measurement results

3.1.1 Micronaire

Table 1 presents the fiber diameter measurements obtained using the Micronaire, where the instrument is calibrated to provide a direct estimate of the average fiber diameter in µm.

Table 1. Fiber diameter measurements obtained by the Micronaire.

Sample	Micronaire reading [µm]
GMW 1	5.10
GMW 2	5.00
GMW 3	5.40
GMW 4	5.40
GMW 5	5.40
GMW 6	5.10
GMW 7	4.90
GMW 8	5.30
GMW 9	4.90
GMW 10	4.40

3.1.2 Diamscope

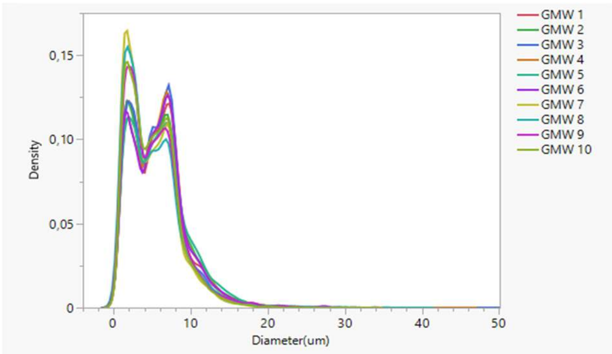
Table 2 presents the fiber diameter measurements obtained using the Diamscope. For each sample, the median, arithmetic mean, and geometric mean fiber diameter were determined. The reported value represents the average of five replicates.

Table 2. Fiber diameter measurements obtained by the Diamscope.

Sample	Median [µm]	AMD [µm]	GMD [µm]
GMW 1	5.41	5.65	4.52
GMW 2	5.04	5.29	4.23
GMW 3	5.30	5.50	4.45
GMW 4	5.62	5.80	4.67
GMW 5	5.57	5.96	4.71
GMW 6	5.57	5.77	4.61
GMW 7	4.57	4.83	3.82
GMW 8	5.08	5.48	4.29
GMW 9	4.10	4.77	3.67
GMW 10	4.37	4.92	3.79

For each sample, the length-weighted fiber diameter distribution was plotted, as shown in Figure 1.

Figure 1. Fiber diameter distributions of samples measured by the Diamscope.



3.1.3 Electron microscopy

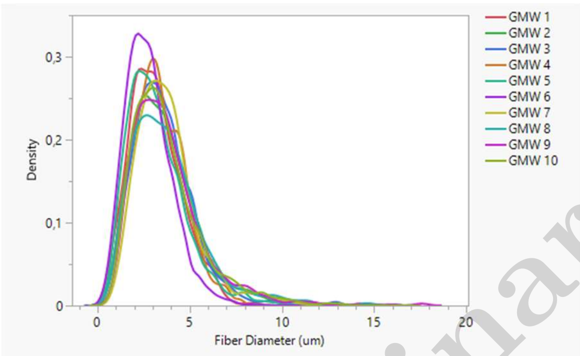
Table 3 presents the fiber diameter measurements obtained by scanning electron microscopy. For each sample, the median, arithmetic mean, and geometric mean fiber diameters were determined. The reported value represents the average of two sample parallels, with two areas analyzed per sample stub.

Table 3. Fiber diameter measurements obtained by scanning electron microscopy.

Sample	Median [µm]	AMD [µm]	GMD [µm]
GMW 1	3.00	3.17	2.83
GMW 2	3.34	3.65	3.23
GMW 3	3.34	3.58	3.20
GMW 4	3.19	3.32	3.01
GMW 5	2.93	3.20	2.83
GMW 6	2.64	2.80	2.50
GMW 7	3.43	3.80	3.37
GMW 8	3.44	3.81	3.33
GMW 9	3.53	3.82	3.46
GMW 10	3.34	3.74	3.32

For each sample, the length-weighted fiber diameter distribution was plotted, as shown in Figure 2.

Figure 2. Fiber diameter distributions of samples measured by scanning electron microscopy.



3.2 Airflow resistivity measurements and calculations

Prior to measurement, the samples were cut into cylindrical specimens, and the mass and thickness of each specimen were recorded. Bulk density, ρ, was then calculated from the measured mass and thickness, t, as shown in Table 4. During measurement, each specimen of defined size and mass was placed inside the measuring tube and exposed to air pressure. The airflow resistivity, σ_m, was reported as the average of several measurements.

Table 4. Measured airflow resistivities, thicknesses and bulk densities.

Sample	σ_m [kPa·s/m^2]	t [mm]	ρ [kg/m^3]
GMW 1	5.80	120	13.02
GMW 2	5.40	135	14.50
GMW 3	6.20	100	14.76
GMW 4	9.10	45	16.87
GMW 5	7.50	200	17.18
GMW 6	9.40	85	18.95
GMW 7	14.20	200	23.15
GMW 8	18.60	120	29.83
GMW 9	26.70	140	31.61
GMW 10	29.40	180	32.26

For each sample, the airflow resistivity was also calculated according to Equation 1 using the densities given in Table 4. For the calculation of the predicted airflow resistivity, σ_c, only the arithmetic mean fiber diameter was used for all fiber diameter measurement methods, in order to maintain consistency with the original approach of Bies and Hansen.

However, as shown in Figures 1 and 2, the arithmetic mean does not necessarily provide the most representative description of the fiber diameter distribution for all samples, particularly when the distribution is skewed or non-normal. In such cases, other statistically derived diameter measures, such as the median or geometric mean, may describe the distribution more appropriately. Nevertheless, to ensure comparability with the Bies–Hansen model in its original form, the arithmetic mean diameter was selected in this study. It should be noted, however, that any statistically derived fiber diameter may be used in the equation, depending on the purpose of the analysis and the nature of the fiber diameter distribution.

Table 5. Comparison of calculated airflow resistivity according to fiber diameter measurement technique.

Sample	σ_c [kPa·s/m^2]		
	Micronaire	Diamscope	SEM
GMW 1	6.20	5.05	16.06
GMW 2	7.61	6.80	14.28
GMW 3	6.70	6.46	15.25
GMW 4	8.22	7.13	21.76
GMW 5	8.46	6.94	24.08
GMW 6	11.02	8.61	36.55
GMW 7	16.21	16.68	26.95
GMW 8	20.42	19.10	39.52
GMW 9	26.11	27.55	42.96
GMW 10	33.40	26.71	46.23

Table 1-3 show that fiber diameters obtained by different measurement methods vary considerably, which in turn leads to different calculated airflow resistivities, shown in Table 5. A comparison of the fiber diameter distributions obtained by the Diamscope and SEM (Figure 1 and 2) also demonstrates that the two methods do not produce identical distributions. As a result, the statistically derived fiber diameter values used in the calculations also differ.

The airflow resistivities calculated from the different fiber diameter measurement methods were compared with the values measured using the Airflow Resistivity Meter in order to assess the agreement between predicted and measured results, shown in Table 6. The Diamscope derived fiber diameters produced airflow resistivity values that showed the closest agreement with the measured data, as indicated by the low absolute differences between calculated and measured values among the methods used in this study. The Micronaire results were less consistent, with slightly higher absolute differences of up to 4 kPa · s/m^2. In contrast, when SEM derived fiber diameters were used in the Bies–Hansen equation, the calculated airflow resistivities were generally overestimated.

Table 6. Comparison of absolute difference between calculated and measured airflow resistivity according to fiber diameter measurement technique.

Sample	$\mid \sigma_m - \sigma_c \mid$ [kPa·s/m^2]		
	Micronaire	Diamscope	SEM
GMW 1	0.40	0.75	10.26
GMW 2	2.21	1.40	8.88
GMW 3	0.50	0.26	9.05
GMW 4	0.88	1.97	12.66
GMW 5	0.96	0.56	16.58
GMW 6	1.62	0.79	27.15
GMW 7	2.01	2.48	12.75
GMW 8	1.82	0.50	20.92
GMW 9	0.59	0.85	16.26
GMW 10	4.00	2.69	16.83

These findings highlight the importance of the fiber diameter measurement method when applying the Bies–Hansen model. However, the closer agreement obtained with the Diamscope or Micronaire does not necessarily mean that these methods provide a more accurate measurement of the true fiber diameter than SEM. Rather, it indicates that the diameter values obtained by these methods are more compatible with the assumptions and empirical basis of the Bies–Hansen model and therefore lead to predicted airflow resistivities that are closer to the measured values.

It is also important to recognize that neither the measured nor the calculated airflow resistivity values can be regarded as exact. Uncertainty arises from the limitations of the airflow resistivity measurement itself, as well as from the determination of input parameters such as density and fiber diameter. In addition, the non-homogeneous nature of the samples and variations in density distribution within the material further contribute to the observed discrepancies. These factors should be taken into account when interpreting the results and when applying the findings in practice.

4. Conclusions

The airflow resistivity of different fibrous material samples was investigated both experimentally and by calculation. Airflow resistivity was first measured using the Airflow Resistivity Meter and was then predicted from the measured bulk density and fiber diameter using the Bies–Hansen model. Fiber diameter was determined using three different measurement techniques, and the arithmetic mean fiber diameter was used in the equation in order to remain consistent with the original Bies–Hansen approach.

The results show that the choice of fiber diameter measurement technique has a clear influence on the predicted airflow resistivity. The different methods produced different fiber diameter values and, consequently, different calculated airflow resistivities. Among the techniques used in this study, the optical method, Diamscope, provided the best agreement with the measured airflow resistivity values. These findings demonstrate that the method used for fiber diameter determination is an important factor when applying the Bies–Hansen model.

The results also suggest that the empirical constants in the Bies–Hansen model may be influenced, at least indirectly, by the fiber diameter measurement technique. This is an important point, because closer agreement between predicted and measured airflow resistivity does not necessarily mean that one fiber diameter measurement method is inherently more accurate than another. Rather, it may indicate that a given method is more compatible with the assumptions and empirical basis of the model.
It is also important to emphasize that a lack of close agreement between predicted and measured airflow resistivity does not mean that a particular fiber diameter measurement method is unsuitable. Instead, it indicates that the differences associated with the selected measurement technique should be taken into account when interpreting the predicted values.

Future research could focus on recalculating the empirical constants, K1 and K2, for each fiber diameter measurement method in order to improve the agreement between calculated and measured airflow resistivity. At the same time, the limitations and uncertainty of the airflow resistivity measurement itself must also be considered, as these contribute to the overall variability of the results.

References

[1] D. A. Bies, C. H. Hansen: “Flow resistance information for acoustical design,” in *Applied Acoustics,* (The University of Adelaide, Adelaide, Australia), no. 13, pp. 357–391, 1980.

[2] A. I. Hurrell, K. V. Horoshenkov, M. T. Pelegrinis: “The accuracy of some models for the airflow resistivity of nonwoven material,” *Applied Acoustics*, no. 130, pp. 230-237, 2018.

[3] DIN EN ISO 9053-1 March 2019: "Acoustics - Determination of airflow resistance – Part 1: Static airflow method (ISO 9053-1:2018).