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Measurement of the bulk acoustic properties of fibrous materials at high temperatures

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ABSTRACT

It is common for fibrous porous materials to be used in high temperature applications such as automotive and gas turbine exhaust silencers. Understanding the effect of temperature on the acoustic properties of these materials is crucial when attempting to predict silencer performance. This requires knowledge of the bulk acoustic properties of the porous materials and so this article aims to quantify the effect of temperature on the bulk acoustic properties of three fibrous materials: rock wool, basalt wool and an E-glass fibre. Measurements are undertaken here using a standard impedance tube that has been modified to accommodate temperatures of up to 500 °C. It is shown that measured data for the bulk acoustic properties may be collapsed using a standard Delany and Bazley curve fitting methodology provided one modifies the properties of the material flow resistivity and air to account for a change in temperature. Moreover, by using a previously proposed power law describing the dependence of the flow resistivity with temperature, one may successfully collapse data measured at every temperature and obtain the Delany and Bazley coefficients in the usual way. Accordingly, to predict the bulk acoustic properties of a fibrous material at elevated temperatures it is necessary only to measure these properties at room temperature, and then to apply the appropriate temperature corrections to the properties of the material flow resistivity and air when using the Delany and Bazley formulae.

1. Introduction

The bulk acoustic properties of porous materials play a crucial role in determining how sound propagates within a material. A knowledge of how sound propagates within a material is essential in the study of those applications in which the material is considered to be bulk reacting. Relevant applications include the study of dissipative silencers where it is widely accepted that one must account for the propagation of sound within the material in order to obtain satisfactory estimations of silencer performance. Examples of this approach include automotive exhaust silencers [1–3], and those silencers found in ventilation and gas turbine systems [4,5]. In these applications fibrous materials are normally used and here it is common for the material to be sourced in large quantities, a portion of which is then packed into the silencer carcass. This results in many silencer applications containing relatively large quantities of fibrous materials in which the fibres are randomly aligned, and with a significant range in fibre diameters being common. Therefore, for this type of application the identification of the bulk acoustic properties is challenging and one must rely on averaging the acoustic behaviour over a number of material samples in order to deliver a reliable guide to overall material behaviour. This makes it very difficult to realise a theoretically based approach to identifying the bulk acoustic properties, and here it is common for a number of empirical constants to be necessary in order to obtain good agreement between prediction and measurement [6–8]. Furthermore, even a semi-empirical model developed using empirical constants is unlikely to reproduce accurately experimental measurements taken over a wide range of different material bulk densities and excitation frequencies. Therefore, for dissipative silencers packed with fibrous materials it is usual practice to rely on experimental measurements when identifying the bulk acoustic properties [1–5].

The bulk acoustic properties of fibrous materials are normally written in the form of the propagation constant and characteristic impedance; these properties may be obtained following measurements of surface impedance taken in an impedance tube. In order to accommodate the random nature of a bulk fibrous material it is common practice to measure many samples of a material – generally covering different bulk densities - and to obtain an overall average behaviour through curve fitting. This can be achieved by plotting these measurements using non-dimensional parameters and this was first demonstrated by Delany and Bazley [9], who

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aggregated measurements taken for a number of different fibrous materials and showed that data for the real and imaginary parts of the bulk acoustic properties may be collapsed onto graphs using a non-dimensional parameter based on the flow resistivity of the fibrous materials. A power law regression analysis then delivers eight coefficients for the bulk acoustic properties, which are normally referred to as the Delany and Bazley coefficients. The method of Delany and Bazley is widely used and forms the basis for the majority of empirical models that quantify sound propagation within bulk fibrous materials. Furthermore, this approach to specifying the bulk acoustic properties of a porous material is almost exclusively used in theoretical models for dissipative silencers [1–5]. However, the data reported by Delany and Bazley, and the vast majority of the studies that have followed, are limited to the measurement of the bulk acoustic properties at room temperature. This presents a problem when attempting to predict dissipative silencer performance at elevated temperatures, because there is little data available to indicate how higher temperatures will affect the acoustic performance of these materials. This is particularly problematic for high temperature silencer applications, such as automotive and gas turbine exhaust silencers, and here it is noticeable that studies have yet to appear in the literature that attempt to predict silencer performance at higher temperatures. A likely reason for this is the absence of comprehensive and reliable data for the bulk acoustic properties of fibrous materials at higher temperatures. Accordingly, this article seeks to address this by reporting impedance tube measurements of the bulk acoustic properties of fibrous materials at elevated temperatures.

Numerous studies are available that report the measurement of the bulk acoustic properties of fibrous materials at room temperature, as well as their use in the design of dissipative silencers [1–5]. It has also long been known that one must correct for errors in the Delany and Bazley coefficients if one is attempting to extrapolate data to low frequencies [10,11]. The bulk acoustic properties are normally obtained from surface impedance measurements carried out according to the European Standard EN ISO 10534-2:2001 [12]. This standard specifies details of the impedance tube and the transfer function measurements required to find the surface impedance of the porous sample. The bulk acoustic properties are then found from two separate impedance measurements, which may be achieved by using, for example, two different air gaps behind the sample, or two different thicknesses [13]. It is this post processing of the surface impedance measurements that delivers the bulk acoustic properties of the material, which are very different to surface impedance, or absorption coefficient, often quoted in the literature for porous materials [14]. Following the measurement of the flow resistivity of the porous material [15] one may then obtain the Delany and Bazley coefficients [9]. The influence of temperature on the bulk acoustic properties coefficients has, however, yet to be explored in detail. This is, perhaps, not surprising given the challenge of undertaking impedance tube measurements at high temperatures. However, Sun et al. [14] recently introduced an experimental apparatus in which it was demonstrated that the surface impedance measurements can be obtained reliably at higher temperatures. This approach is also well suited to obtaining experimental measurements of the bulk acoustic properties, and so the apparatus described by Sun et al. will form the basis of the experimental investigation that follows.

There are very few studies in the literature that attempt to quantify the influence of elevated temperatures on the acoustic properties of fibrous materials and, to the best of the authors' knowledge, no studies that measure the bulk acoustic properties at high temperatures using an ISO 10534-2 standard test rig [12]. The first study on the effect of high temperatures was carried out by Christie [16], who measured the Delany and Bazley coefficients for mineral wool at 19 °C, 255 °C and 490 °C. Christie used a closed cavity experimental apparatus in order to raise the temperature of the fibrous material, and here it is not entirely clear how accurate this experimental apparatus is likely to be, and it does not, of course, comply with later ISO standards. Christie also measured the flow resistivity of the material over a range of temperatures up to and including 700 °C, and here Christie found an increase in the flow resistivity of the material proportional to the 0.6th power of the (absolute) temperature for temperatures up to about 400 °C. Above this temperature the rate of increase begins to slow down and this power law no longer fits Christie's experimental data. Christie then compared values for the bulk acoustic properties measured at high temperatures with those predicted using Delany and Bazley's coefficients, after first modifying the flow resistivity to account for the higher temperatures. Christie demonstrated reasonably good agreement between the two results and concluded that the power law relationship for the flow resistivity was successful, at least over the temperature range of the acoustic measurements. However, Christie only measured data at two elevated temperatures and reports little data with which to substantiate the final conclusions; agreement between data measured at high temperatures and that predicted using the Delany and Bazley coefficients is also limited at certain frequencies. Therefore, one cannot be certain that the discrepancies evident in Christie's results are not caused by a departure of the material properties from those measured by Delany and Bazley, or by experimental error. Here, a question mark also remains over the accuracy of the experimental methodology for the acoustic measurements, especially as the design of the apparatus departs significantly from current practice [12]. Furthermore, Christie does not measure a sufficient amount of data in order to obtain a representative average behaviour for the material. Thus, the measurements provided by Christie are too limited to provide confidence in the method used to extrapolate the data of Delany and Bazley to higher temperatures. Nevertheless, Christie's findings are interesting, especially as there is a clear and obvious advantage to using the power law relationship proposed for the material flow resistivity, as this would permit the Delany and Bazley coefficients measured at room temperature to be used at higher temperatures without actually measuring the acoustic properties at higher temperatures.

The power law profile for flow resistivity proposed by Christie [16] was later investigated by Giese et al. [17], who used a microstructure model to investigate the influence of temperature on the acoustic properties of a fibrous material. Giese et al. predict modifications to the material flow resistivity that are similar to those proposed by Christie, although no experimental data was obtained to support these conclusions. Recently, high temperature measurements were also undertaken by Sun et al. [14], who used an ISO standard impedance tube to obtain measurements of surface impedance up to a temperature of 500 °C. Sun et al. were interested in the surface impedance of a thin disk of steel wool and showed that the absorption coefficient of this material decreased when the temperature increased, at least up to a frequency of about 5 kHz. Sun et al. [14] also demonstrated good agreement between measured and predicted absorption coefficient using a microstructure based theory. This approach allowed Sun et al. to investigate the influence of temperature on those parameters typically used in theoretical models for porous media. However, Sun et al. did not proceed to measure the bulk acoustic properties of the porous material and here it is likely to be difficult to extend their theoretical approach to the investigation of the propagation constant and characteristic impedance. This is because it is likely to be more challenging to obtain good agreement between prediction and measurement for the propagation of sound within random bulk samples of a fibrous material, when compared to the surface impedance of a thin rigid disk of material.