Development of new Device for Measurement of Airborne Fiber Concentration

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ABSTRACT
Devices for the measurement of airborne fiber concentration currently existing on the market show significant disadvantages. Due to e.g. multi-step measurement principles or bulky design, existing devices are not capable to be used for specific applications.

Knowledge of airborne fiber concentration is essential to determine operation conditions and air quality in e.g. textile mills, museums or operating rooms in hospitals. This paper presents a new measurement device according to VDI standard 2221. The device consists mainly of a converging duct, an exhaust system and an optical sensor. Preliminary trials prove the functionality of the developed fiber measurement system.

INTRODUCTION
According to [1] fibers are defined as long stretched particles with the following characteristics:
- Length \( L > 5 \mu m \)
- Thickness \( T < 3 \mu m \)
- Length / thickness ratio \( L/T > 3:1 \)

The measurement of airborne fiber concentration is essential for determination of air quality. For example the former use of asbestos as construction material did show that there is a need of an adequate measurement system. Inhalation of asbestos fibers can cause lung diseases such as asbestosis or lung cancer as well as a special type of breast cancer or peritoneum (mesothelioma) [2]. Therefore, the exposure of the population by airborne asbestos fibers must be kept as low as possible. Although the natural release of asbestos fibers from rocks cannot be controlled, it is possible to prevent the release of the fibers into the air, or to reduce it in the technical usage of asbestos fibers.

Also in textile factories, airborne fibers lead to the pollution of objects and clothes and can irritate the skin or interfere with breathing. For certain substances there is a risk of allergies, poisonings or cancer. Also textile mills processing carbon fibers need to know about the amount of airborne carbon fibers since this fiber material is highly conductive [2]. Moreover, visitors’ clothing can be a source of fibers and dust in museums [3] [4] or operating rooms in hospitals and therefore affect the air quality.

For that reason, this paper will present an easy to handle device for the measurement of airborne fiber concentration.

STATE OF THE ART
A principle to determine airborne fiber concentration is based on VDI standard 3492 [5].

Here the air flow is lead through a specially designed sampling device. The sampling device consists of a gold-sputtered capillary pores membrane filter made of polycarbonate. The gold layer is required primarily for the dissipation of electric charge while a scanning electron micrograph image of the filter is made. The gold layer ensures that there is no change of the geometric dimensions of the fibers which are collected on the filter during the examination. The intake of air itself takes about eight hours and is followed by an SEM examination of the mentioned filter. Thus it is manually investigated whether the intake of air through the filter led to depositing of fibers on its surface. For this purpose, the SEM image of the filter is enlarged by a factor of 2000 to count the fibers and to measure the corresponding fiber length. Counting of the fibers follows special rules published by the World Health Organization [6].

Fiber concentration \( C \) is calculated with the following information:
- Result of fiber counting
- Surface area of the filter medium
- Analyzed volume of air

Finally, fiber concentration \( C \) results from:

\[
C = \frac{n}{V_a}
\]
where \( n \) is the counted amount of fibers and \( V_A \) is the analyzed volume of air [m\(^3\)]. The analyzed volume of air is calculated by:

\[
V_A = \frac{V \cdot N \cdot A_B}{\pi \cdot r_{\text{eff}}^2}
\]

(2)

where \( V \) is the air sample volume (volume of air led through the filter) [m\(^3\)], \( N \) is the amount of investigated filters, \( A_B \) is the surface area of the filter [mm\(^2\)] and \( r_{\text{eff}} \) is the effective filter radius [mm].

A significant disadvantage of this approach is the costly and time-consuming method of analysis by SEM. In addition to this, the sampling equipment is complex. The airborne fiber concentration cannot be displayed immediately. Thus, measurement and evaluation are carried out at different locations and at different times. An advantage is the high accuracy of the method. Additionally, SEM analysis is also capable of identifying different fiber materials.

CertainTeed Corp., Valley Forge, Tennessee patented an optical process for the determination of airborne fiber concentration in 1999 [7]. A vacuum pump draws in room air through two tubes that form the flow channel. The intake air flow as well as the lengths and diameters of the tubes are chosen so that a laminar flow is formed. Due to this laminar flow, airborne fibers align parallel to the center line of the tubes. A light source, e.g. a laser diode, emits a light beam. This beam passes through the nip to the lens assembly and finally to the light sensor. Fibers passing through the beam cause a scattering pattern of emitted light.

The scattered light from the fibers will now be focused by paired condensing lenses on the light sensor. The lenses amplify the scattered light from the fibers. By measuring the scattered light, a better sensor response is achieved. When the light sensor detects the incidence of scattered light, the sensor sends an electrical pulse to the measuring unit. Afterwards the fiber content of the intake air stream is calculated and displayed in real-time.

A major advantage of this approach is the direct display of the fiber concentration in the collected air.

The complex construction of the apparatus is, however, a disadvantage. The dimensions of the tubes have to be determined experimentally so that a precise laminar flow occurs in the flow channel. Only this way it can be guaranteed that the fibers align perpendicular to the emitted light beam. The vertical orientation of the fibers is in turn necessary for a valid measurement of light scattering. Furthermore, the lens should be placed so that the focusing of scattered light is amplified not decreased. The noisy vacuum pump affects the user during the measurement and is an uncomfortable peripheral device.

A possibility for real-time measurement of airborne fiber concentration is provided by MIE Inc., Bedford, USA. The Fiber Monitor FM-7400 takes in ambient air and aligns existing airborne fibers with an oscillating electrical field [8]. When aligned by the electrical field, the fibers pass a laser barrier. The signal scattered by the fibers is measured in order to calculate the airborne fiber concentration.

The major advantage of FM-7400 in comparison to the other concepts mentioned above is real-time measurement. Computed results of airborne fiber concentration are immediately displayed so that the user can directly react on critical values. Only fibers up to a length of 20 µm can be detected by this device which is a serious disadvantage. Furthermore, the Institute for Occupational Safety and Health of the German Social Accident Insurance (IFA), Berlin, Germany has performed a long-term testing of FM-7400 [9]. As a result, IFA found out that the device continuously underestimates the airborne fiber concentration and explicitly advises against using the FM-7400 because of invalid results.

Table I summarizes the advantages and disadvantages of the presented measurement principles.

### DESIGN AND SENSOR SYSTEM

Aim of the presented work is the design of a measurement device overcoming disadvantages of the existing solutions. The construction parameters essentially refer to the design method described in the VDI standard 2221 [10]. The measurement device should take in a defined air volume.

<table>
<thead>
<tr>
<th>Measurement Principle</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td>VDI 3492</td>
<td>High accuracy, detection of different types of fibers</td>
<td>Multi-step process, no immediate measurement result, high cost for components and specimen,</td>
</tr>
<tr>
<td>Certain Teed Cooperation</td>
<td>Immediate measurement result, continuous measurement process</td>
<td>Complex design, noisy vacuum exhaust system</td>
</tr>
<tr>
<td>MIE Inc., FM-7400</td>
<td>Real-time measurement, portable device</td>
<td>Underestimation of airborne fiber concentration, German IFA explicitly advises against using the device</td>
</tr>
</tbody>
</table>

The output should result in the amount of fibers per cubic meter of air. All possible types of textile fibers that can be found in the air should be detected and counted. Furthermore, the measurement device must
consist of components which allow a valid determination of the fiber content in intervals of about 30 minutes. These components must have a very low design effort to achieve a low-cost solution of a measurement device. In addition, the device needs to be freely positionable, mobile and silent. The design of the device has to allow for sterilization to ensure applicability also in hygiene-critical environments. It is therefore necessary to ensure moisture resistance and smooth surfaces. All the requirements for the engineering design of the measurement device are summarized in Table II.

TABLE II. Requirements of the new measurement device.

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geometry</td>
<td>Length: 500 mm</td>
</tr>
<tr>
<td></td>
<td>Width: 120 mm</td>
</tr>
<tr>
<td></td>
<td>Height: 120 mm</td>
</tr>
<tr>
<td>Usage</td>
<td>Silent components</td>
</tr>
<tr>
<td>Measurement</td>
<td>Intervals of 30 minutes</td>
</tr>
<tr>
<td>Displaying</td>
<td>Display in the unit [number of fibers/m³ air]</td>
</tr>
<tr>
<td>Energy</td>
<td>230 V power supply</td>
</tr>
<tr>
<td>Signal</td>
<td>Online measurement, voltage signal in the range ± 10 V</td>
</tr>
<tr>
<td>Security/Hygiene</td>
<td>Smooth surfaces, insensitivity to moisture</td>
</tr>
<tr>
<td>Ergonomics</td>
<td>Free positioning, low weight</td>
</tr>
</tbody>
</table>

A concept based on these requirements uses an optical sensor for the measurement of airborne fiber concentration, see Figure 1.

![Figure 1](image1.png)

FIGURE 1. Concept of a new device for determination of airborne fiber concentration.

To summarize, the following aspects differentiate the developed concept from the state of the art:

- Valid real-time measurement of airborne fiber concentration becomes possible due to a sensor suitable for different fiber types and fiber lengths.
- Sensor system with high scan frequency is selected in order to detect even very short fibers or flock. Fibers with a length on the scale of several millimeters can also be detected.
- Noise emission is reduced to a minimum by using silent components. During a running measurement, the surrounding will not be affected by the device.

A radial fan takes in ambient air which is led through a converging duct. Due to the design of the converging duct, it performs the function of a nozzle and accelerates the sucked air flow. As a result of the acceleration of the air flow, fibers will be stretched and aligned along the converging duct’s axis. Fibers possibly existing in the sucked air flow are detected by a light signal between emitter and receiver. If a fiber passes the light signal, the receiver detects a decrease of signal intensity. The radial fan takes in a defined air volume. Thus, the course of signal intensity over time has to be evaluated in order to calculate the airborne fiber concentration in the required unit [fibers/m³].

For this, the continuity equation can be used:

\[ \dot{V} = c \cdot A \]  

(3)

where \( \dot{V} \) is the air flow volume led through the converging duct [m³/s], \( c \) is the flow rate [m/s] and \( A \) is the cross-section area of the converging duct [m²]. The flow rate \( c_{in} \) at the inlet of the converging duct can be calculated with a given constant air flow volume \( \dot{V} \) as:

\[ c_{in} = \frac{\dot{V}}{A_{in}} \]  

(4)

where \( A_{in} \) is the cross section area of the inlet. Similarly, the flow rate at the outlet of the converging duct can be calculated as:

\[ c_{out} = \frac{\dot{V}}{A_{out}} \]  

(5)
where \( A_{\text{out}} \) is the cross section area of the outlet.

The converging duct assumes the following functions:
- Compression of air
- Leading the air and possibly containing fibers to the point of measurement
- Acceleration of the air flow in order to stretch and align fibers

Furthermore the converging duct is characterized by

\[
A_{\text{in}} > A_{\text{out}} \tag{6}
\]

and therefore

\[
c_{\text{out}} > c_{\text{in}} \tag{7}
\]

The flow rate of the air increases while passing through the converging duct. This effect is essential for the design of the measurement device. Fibers are in general chaotically oriented within the ambient air. Then, by the intake of air through the converging duct, the fibers will be aligned along the axis as shown in Figure 1.

**Sensor Concept**

Airborne fibers are led through the converging duct with a defined flow rate, see Eq. (5). These fibers have to be detected by the sensor. It follows that the flow rate at the outlet of the converging duct is an important indicator for the required scan rate. In the following, the required scan rate of the sensor is calculated.

The cross-section area \( A_{\text{out}} \) of the outlet of the converging duct can be calculated as

\[
A_{\text{out}} = \pi \cdot r_{\text{out}}^2 = \pi \cdot (8\text{ mm})^2 \approx 201\text{ mm}^2 \tag{8}
\]

Together with

\[
\dot{V} = 80\ \text{m}^3/\text{h} \approx 22,2 \cdot 10^6\ \frac{\text{mm}^3}{\text{s}} \tag{9}
\]

as the air flow volume performed by the radial fan, the flow rate at the outlet of the converging duct can be calculated as

\[
c_{\text{out}} = \frac{22,2 \cdot 10^6\ \frac{\text{mm}^3}{\text{s}}}{201\text{ mm}^2} \approx 110448\ \frac{\text{mm}}{\text{s}} \tag{10}
\]

A fiber that needs to be detected by the sensor remains within the measuring zone of the light signal for

\[
t = \frac{w_s + l_f}{c_{\text{out}}} \tag{11}
\]

where \( w_s \) is the width of the light signal and \( l_f \) is the fiber length. The considerations behind Eq. (11) are visualized in Figure 2 and Figure 3, whereas Figure 3 shows the expected signal characteristic resulting from a detected fiber as well.

**Selection of the Sensor**

With regard to Eq. (12) it becomes obvious that the required scan frequency of the sensor depends on the width of the emitted light signal. The flow rate \( c_{\text{out}} \) at the outlet of the converging duct is constant and defined by the radial fan and the geometry of the pipe; see Eq. (5) to Eq. (10). In order to select a suitable sensor, first the provided width of the emitted light signal has to be examined. Secondly, the required scan frequency needs to be calculated by Eq. (12) and compared with the technical data of the examined sensor.

Finally, a sensor system of Sensor Instruments Entwicklungs- und Vertriebs GmbH, Thurmansbang, Germany has been selected. The single components of this sensor system and the prototype of the developed measurement device are shown in Figure 4.
The component SPECTRO-1-FIO [12] emits and receives a white light signal through the fiber optic cables D-S-R2.1-(6x1)-1200-67° [13]. This type of fiber optic cable was selected because it allows for an expansion of the white light signal. Due to the expansion, fiber detection over the entire outlet area of the converging duct is ensured. The optical frontend KL-M34-XL-R2.1 on the emitting cable is used to precisely focus the white light signal at the outlet of the converging duct [13]. The white light signal impinging on the receiver becomes bundled by another optical frontend at the receiving cable. SPECTRO-1-FIO detects the received intensity of the white light signal which is then converted into a voltage signal. The dimensions of the light beam in the inspection area are shown in Figure 5.

Eq. (12) shows that the required scan frequency \( f \) of the sensor is a function of the flow rate \( c_{out} \) at the converging duct’s outlet and the width of the emitted light signal \( w_e \). Since \( c_{out} \) is constant, only the width of the light signal has to be taken into account. The white light signal which is emitted by SPECTRO-1-FIO has a width of

\[
w_e = 2.5 \text{ mm}
\]  

at the converging duct’s outlet. With the flow rate basing on Eq. (10) the required scan frequency of the sensor can be calculated as

\[
f = \frac{110448 \text{ mm}}{2.5 \text{ mm}} = 44180 \text{ Hz} \approx 44.18 \text{ kHz}
\]  

According to [12] SPECTRO-1-FIO has a scan frequency of 200 kHz which is higher than the required scan frequency calculated in Eq. (14). Thus, the selected sensor system is a solution suitable to detect fibers in an air flow under the conditions mentioned in section 3.2.

In the following section, the validation of the measurement device is described.

RESULTS AND DISCUSSION

A preliminary validation trial was performed by the intake of an ideal sphere into the measurement device as shown in Figure 6.

When there is no object in the measuring zone, 100% of the emitted white light signal impinges on the receiver of the sensor system. This results in a raw signal of about 4 V. When the sphere enters the measurement zone, a decrease in signal intensity is detected by the sensor which results in a decrease of the output voltage signal. The slope of the falling and rising edge depends on the velocity of the sphere. Thus, the slope of the edges is an indicator for the flow rate. Due to the constant flow rate, the slope of the falling and the rising edge should be approximately equal. Between about 3 ms and 22 ms, the sphere completely covers the white light signal.

Received signal intensity can either be monitored via the USB interface of SPECTRO-1-FIO and corresponding software or by connecting the signal output to a programmable controller (or the like). USB interface can also be used to parameterize the sensor or to change settings.

The following calculation proves that the selected sensor system builds a solution suitable for the conditions mentioned in section 3.2.
signal. Therefore the signal intensity detected by the receiver falls to zero. After that, the sphere leaves the measurement zone. Thus, the detected white light signal intensity increases continuously up to raw signal level of about 4 V. The distance between the falling and rising edge is therefore an indicator for the length of the detected fiber. One more indicator for the length of a detected fiber can be found in Figure 6. As soon as a fiber enters the measuring zone, it covers a part of the emitted white light. A fiber with a larger volume covers a greater part of the light signal when it is completely located within the light signal than a smaller fiber (see t = 2 and t = 3 in Figure 3).

The preliminary validation trial proved the functionality of the measurement device by detecting an ideal sphere. The resulting signal characteristic fits to the expected characteristic shown in Figure 3.

The measurement device has to be validated further to see whether objects of different dimensions can be detected. In order to do this, polystyrene spheres of three different diameters were sucked into the measurement device. Spheres instead of fibers are passed through the inspection area because fibers might be irregular in shape and orientation. Spheres are considered to be more appropriate for validation trials. Five trials per each diameter were performed consecutively. Each trial consisted of taking a sphere into the measurement device and saving the corresponding signal characteristic. The results of the arithmetic means of the generated signal characteristics are shown in Figure 7.

![Figure 7](https://example.com/figure7.png)

**FIGURE 7.** Signal characteristic gained by the detection of spheres with three different diameters (arithmetic means of five trials per each sphere).

Results show that spheres of the diameters 2 mm, 3 mm and 4 mm can be accurately allocated to the three different signal characteristics. As mentioned above, the distance of falling and rising edge of the signal characteristic was assumed to be an indicator for the fiber length and, in this case, the diameter of the spheres. Furthermore, the depth of the signal peak was assumed to be an indicator for the same. By the results in Figure 7 this assumptions can be confirmed. The signal characteristic with the smallest peak was gained during the detection of a sphere with a diameter of 2 mm. Also the smallest distance between falling and rising edge belongs to the signal characteristic of the smallest sphere examined within the trials. Obviously, the mentioned indicators for the fiber length can be found also in the signal characteristics of spheres with a diameter of 3 mm and 4 mm. Furthermore it is visible that the slope of the falling edges and the rising edges are approximately equal. The spheres enter and leave the measuring zone with a constant velocity which means that a constant flow rate can be established.

**CONCLUSION**

In this work, the development of a device for the measurement of airborne fiber concentration was presented. Based on the deficits of the state of the art, new methods to measure the airborne fiber concentration were developed.

In this paper, the selection of a sensor system suitable for the conditions of detecting airborne fibers is described. Finally, a white light sensor was selected which emits the light signal through fiber optic cables. The light signal is focused on the measurement zone by special optical frontends.

The paper is concluded by analyzing the results of validation trials where fibers of three different lengths were detected by the developed measurement device. Further development steps consist in testing the developed device under real conditions.

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**REFERENCES**


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