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LARGE DROP RE-ENTRAINMENT FROM AN OIL-MIST FILTER

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ABSTRACT

This work details the development and calibration of a novel device to measure re-entrainment from oil-mist or coalescing filters. Oil drops with a size of up to several hundred microns are often blown-off from oil-mist filters. Once re-entrained, they impact on the filter housing and hence they are transported along the tubing as undesired "wall flow". To detect these large drops a light-sheet device was developed. A laser beam is expanded to form a sheet directly behind the filter. The light scattered by the drops which blow off the filter and pass through the optically defined measurement volume, is detected using a photomultiplier. The height of the signal of an individual drop corresponds to its size. However, several drops are usually released from the filter at almost the same time. Thus, the detected signal is a superposition of the signals of individual drops. To obtain the height, and hence size of the individual drops, an advanced data analysis for noise reduction, peak finding and peak fitting was necessary. The setup of the light-sheet device, its size calibration and the signal analysis are discussed.

KEYWORDS

Mist Filtration, Coalescence Filter, Drop Re-entrainment, Optical Particle Measurement

1. Introduction

Oil-mists, i.e. small aerosol droplets with a typical size of a few hundred nm are generated by many industrial processes, including engine crankcase ventilation and generation of compressed air by oil lubricated compressors. It is necessary to remove these mists to avoid problems further downstream or to meet health and safety regulations. The most common method for removing these mist droplets from an air stream is the use of fibrous filters. Mist droplets are deposited on the fibres due to diffusion, interception or inertial impaction (Brown, 1993). As more and more droplets are captured by a fibre, they coalesce into larger drops (Yarin et al., 2006). Then these large drops are transported to the rear of the filter, where they usually drain. However, conditions can be such that they are partly blown off the filter with a size of several hundred microns up to a millimetre and re-entrain into the clean gas. Then they impact on the filter housing and hence they are transported along the tubing as wall flow. By this mechanism, known as re-entrainment, a much larger amount of oil can be generated at the clean gas side, than by direct penetration.

To detect these large re-entrained oil drops, it is not possible to introduce them into a measurement device, since at each deflection of the sampling line, such large drops would immediately impact on the walls. To characterize such drops, there exist several in-situ methods. Planar Mie scattering interferometry (Damaschke et al., 2002) is usually used to characterize sprays. Since this method uses a pulsed laser at a fixed repetition rate, a continuous or periodic drop source is required. The drops blown-off an oil mist filter, however, appear randomly. Hence these systems are unsuitable for the detection of re-entrained drops. Phase-Doppler measurements (Bachalo and Houser, 1984) could provide the particle size and velocity but these systems are costly. For this reason a device based on a light-sheet technique, which is more suitable for the measurement of the re-entrainment was developed.

2. Experimental setup

The concept of the light-sheet device is, to expand a laser beam to form a plane directly after the filter (Fig. 1). When re-entrained drops pass through this light-sheet, they generate scattered light, which is detected by a photomultiplier. This signal is converted via a software procedure to the particle size.

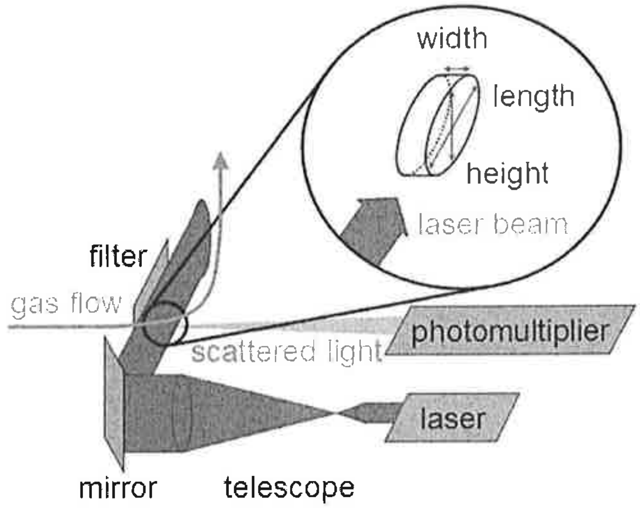

Figure 1: Overview of the experimental setup. The laser beam is expanded by a telescope to a light sheet, which is placed directly behind the filter. Drops blown off the filter and hence passing through the light sheet generate scattered light, which is detected by a photomultiplier. An aperture in front of the photomultiplier determines the measurement volume (magnification).

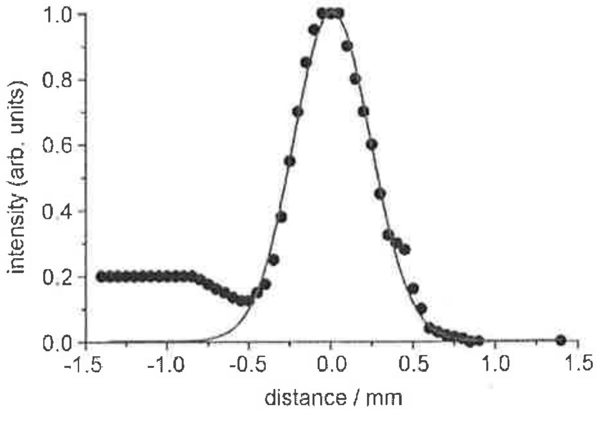

Figure 2: From the scattered light intensity measured with a steel sphere mounted on a rod represents the TEM00-mode of the laser, the width of the measurement volume for each particle size can be read off. The background data on the left side of the peak are due to the rod on which the sphere was mounted.

A cw-Argon-Ion-Laser with principle wave lengths of 488 nm and 515 nm at a power of 60 mW was used. Its Gaussian TEM00-mode was expanded in one direction by a factor of 60 in width using a telescope with cylindrical lenses. The expanded laser beam passes directly behind the rear face of the filter and ends in a light trap. A circular aperture is placed in front of the photomultiplier to define the measurement volume. Hence only light from this optically defined measurement volume, which is scattered under the angle of 90° ± 0.7° is detected. To measure the dimension of the measurement volume in the flow direction, a steel sphere mounted on a rod is periodically inserted through the light-sheet. The measured intensity of the scattered light reflects well the Gaussian beam profile (Fig. 2). Thus, for a specific particle size and hence signal intensity, the width of the measurement volume is determined. To measure the other dimensions of the measurement volume, the horizontal and vertical position of the steel sphere on the rod, respectively, are varied. The intensity of the scattered light perpendicular to the airflow and perpendicular to the laser beam shows the almost flat top of the expanded Gaussian beam profile (Fig. 3 left), whereas the profile in the laser beam direction is constant (Fig. 3 right), since the telescope was adjusted in such a way that the laser beam has no divergence. The steep edges of the width and length of the measurement volume are due to the aperture in the observation optics.

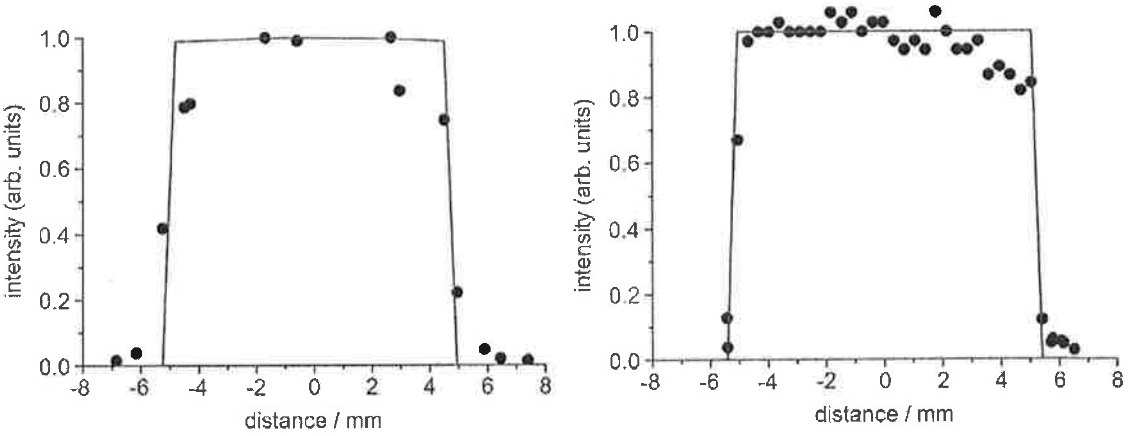

Figure 3: The scattered light signal of a steel sphere reflects the flat top of the expanded Gaussian beam profile over the height of the measurement volume (left), whereas the signal intensity is independent within the length of the measurement volume (right).

2. Signal processing

For the present re-entrainment process, a simple on-line data analysis method which only determines the peak of the signal is not sufficient, since peaks from different drops frequently overlap. Consequently, a more complex data analysis, which could not be performed on-line, is required to extract the individual peaks from the entire signal. Hence it is necessary to write the data from the photomultiplier (PMT) to the hard disk with a PC-oscilloscope. The software logs only the signals, which pass a user defined trigger threshold (200 mV in Fig. 4). These signals are then processed using a macro in the "root" software package (root.cern.ch). Computing the 35th order median of the signal helps to eliminate the majority of the noise (Fig. 4). The signal then is transformed to Fourier space to cut off the high frequencies with a Fermi filter. Afterwards the signal is transformed back to real space. Finally the individual, usually overlapping peaks are extracted by a deconvolution based method and then the individual peaks are fitted. Hereby all peaks below a fit threshold (30 mV in Fig. 4) are discarded. Hence there are three types of signals, which are treated differently:

- All peaks below the fit threshold (30 mV) are discarded.
- Peaks above the fit threshold (30 mV) and below the detection threshold (200 mV) are detected only if they come along with peaks above the detection threshold (200 mV), within a user defined time window (typically 1.5 ms).
- Peaks above the detection threshold (200 mV) are all detected.

Using this method, the complexity of the complete signal is reduced to the number of peaks found times the three parameters characterizing a Gaussian peak. The condensed data can be easily processed using additional software, which allows the evolution of the re-entrained drop size distribution to be obtained.

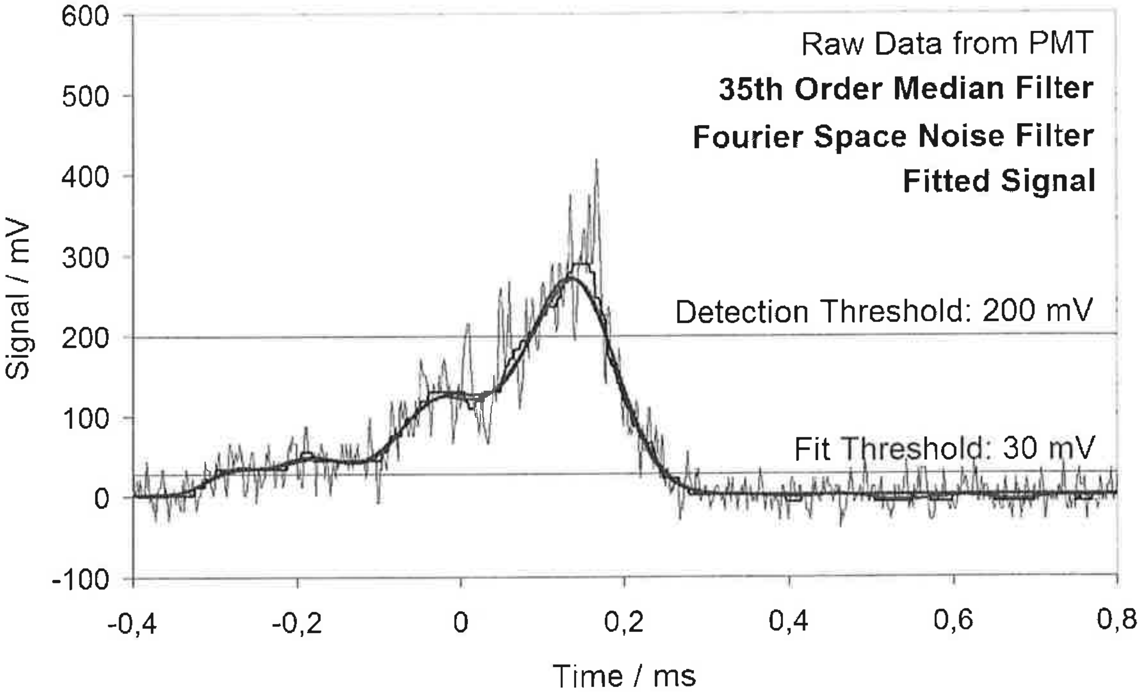

Figure 4: Each signal above the detection threshold (200 mV) is detected. The noise of the raw data from the photomultiplier (PMT) is eliminated by first applying a median filter in real space and then a Fermi filter in Fourier space. The fit of a superposition of Gaussian peaks to this noise reduced signal does not differ much from the noise reduced signal itself. All peaks below the fit threshold are discarded.

3. Calibration

To convert the voltage delivered by the photomultiplier into a particle size, a calibration is necessary. Since the detected particles are much larger than the wavelength of the scattered light, the laws of geometrical optics apply. Then the intensity of the scattered light is proportional to the square of the particle size (Gebhardt, 1993), hence the calibration curve, which relates the PMT voltage to the particle size is a parabola.

The most direct way of calibration would be the use of large oil drops of exactly known size. Large liquid drops could be generated for instance by a jet dispensing device. Its working principle is based on a vibrating piezo crystal, which generates a pressure wave in a liquid column. This results in a periodical emission of liquid drops from the nozzle. However, using this method produces several drops in the measurement volume at the same time, so that a size calibration is not possible.

Consequently, a steel sphere mounted on a rod, which moves periodically into the measurement volume was used. At the surface of the steel sphere, the light is only reflected, whereas for transparent particles, such as oil drops, light is also refracted. The refracted light is reflected and refracted again at the next interfaces of the same drop (Fig. 5 left). This yields different scattering modes, which add to the total signal of scattered light. The intensity of the modes can be calculated using the Fresnel formulas. The material properties are taken into account by the refractive index. Hence, from the measured calibration curve for steel the calibration curve for oil can be calculated (Fig. 5 right).

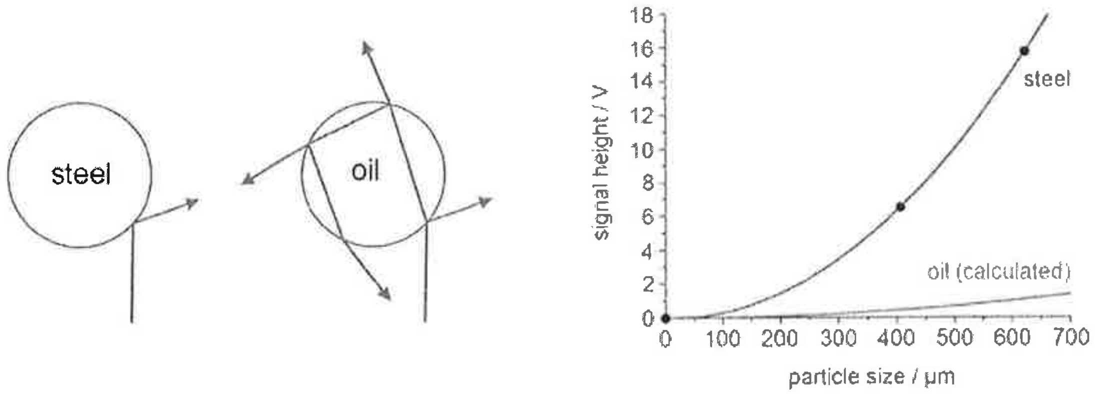

Figure 5: Calibration with steel spheres. To calculate the calibration curve of oil from the calibration curve of steel (right), different refraction modes have to be considered (left).

When measurement of “real” re-entrainment from an oil-mist filter is performed with this calibration, the overall mass balance is inconsistent with gravimetric measurements. The optically measured re-entrained particles are oversized. Therefore the calibration with steel spheres seems unreliable. For this reason the calibration will be redone using a calibration based on re-entrained mass of oil. The re-entrained mass can be measured gravimetrically when the blown-off drops are collected into a receptacle. On the other hand, the optical re-entrainment measurement also provides the total re-entrained mass, provided that a calibration factor for the conversion from voltage to particle size is applied. This calibration factor was chosen in such a way, that both masses (the gravimetrically determined amount of oil and the optically measured re-entrained mass) match. An arbitrarily assumed error in mass of 10% (since smaller drops are detected only if they coincide with larger drops above the detection threshold and thus, are underestimated) results in an overestimation of the optically measured droplet size by about 3%.

Border zone errors of the optical system have not yet been mentioned. These could consist of two types of error:

1. Completely illuminated particles, which are at the border of the measurement volume (hence their light is not completely detected).
2. Particles which are completely in the measurement volume, but at the border of the light sheet (hence they are not completely illuminated).

Type 2 errors were not present in this case, since the light sheet fully illuminates the measurement volume. The cross section of the measurement volume is circular, about 1 cm in diameter. Hence for a particle of 0.2 mm, the border zone is less than 10% of the full area. For smaller particles the border zone error is further reduced. For this reason the border zone error is neglected. Advanced elimination methods (Umhauer, 1983, Lindenthal and Mölter, 1998) were not implemented in the setup and a correction (Borho, 1970) for this effect has not been applied.

5. Conclusions

A device to detect large, sub-millimetre sized drops based on a light-sheet technique with an optically defined measurement volume was constructed. Advanced signal processing consisting of a Fermi filter to remove noise and a peak finding and fitting algorithm allows individual peaks to be extracted from the measured signal, which usually is a superposition of patterns from several drops. The calibration of the device with steel spheres was found not to deliver the correct particle size and it was therefore decided to calibrate the device via the overall re-entrained mass, producing good results.

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