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## **Empirical Protocol to Correct Laser-Diffraction Measurements from Multiple-Scattering Effects**

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### **Abstract**

The present work addresses the problem of multiple-scattering effects on Laser-Diffraction spray drop-size distribution measurements. The Laser-Diffraction Technique (LDT) is a rather straightforward diagnostic often used in industries and universities to characterize liquid sprays. Recent LDT equipments have been especially conceived for highly transient and dense sprays such as those encountered in car injection applications (direct gasoline injection or diesel injection). In particular, they are equipped with an optional algorithm to correct the effects of multiple-scattering that occurs when the spray density is great. However, experimental investigations of the literature reported that this algorithm was not able to treat all situations. An explanation for this could be found in the assumptions of the model that are often not satisfied by real sprays. For several years, an alternative to this approach has been explored: it consists in establishing an empirical correction protocol. In a recent approach, this empirical correction protocol received a mathematical description. The work in the present contribution generalizes this mathematical model and demonstrates that it is able to describe the influence of multiple-scattering for other working conditions. The sprays investigated here are produced by a three-jet gasoline direct injection device. We found that the mathematical model was adaptable to this case. Therefore, the present empirical correction protocol appears to be easily applicable and should be recommended at least to test a theoretical model or at most to replace it.

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### **Introduction**

The laser diffraction technique (LDT) is an optical diagnostic often used to measure drop-diameter distribution of liquid sprays. (Many references detail its principle of working, i.e., [1, 2] for instance.) The LDT performs a line-of-sight measurement: the optical probe is a cylindrical laser beam whose diameter is of the order of a few millimeters, and each drop going through this probe participates to the measurement unless it is too far from the Fourier lens that focuses the forward diffracted light on a set of diodes positioned at the focal length. The scattered-signal distribution recorded by the series of diodes is directly dependent on the diameter distribution of the droplets of the spray: the LDT reports the drop-diameter distribution of the spray that would produce the same forward diffraction pattern as the one recorded.

Recent LDT equipments (such as the Spraytec series from Malvern for instance) have been designed to meet the requirements imposed by high-injection pressure transient injection devices: they allow high acquisition rate to be reached and are equipped with a multiple-scattering correction algorithm that is advised to select when dense or large sprays are probed.

The basic mathematical inversion procedure that calculates the drop-diameter distribution from the forward light-diffraction measurement assumes individual photons scattering off single particles. This assumption is acceptable when the number of drops in the optical probe is sufficiently low. If not, a significant number of photons are scattered more than once. As a consequence the diffraction angles are increased and this behavior is interpreted as an increase of the small drop population. Therefore, as reported by several experimental investigations [3-11], multiple-scattering effects overestimate the small drop population and underestimate the width of the distribution. These investigations found also that 40-50% is the transmission limit under which multiple-scattering affects LDT measurements. (The transmission is the ratio of the undiffracted light intensity on the incident light intensity.)

The problem caused by multiple-scattering has motivated numerous theoretical investigations to derive competent models to correct LDT measurement from these pejorative effects (see review in [11]). These models assume isolated particle light scattering and spray characteristics (concentration and drop-diameter distribution) uniformly distributed in space. In high spatial density real sprays, these two assumptions are never satisfied. This might explain that experimental investigations reported a poor ability of such models to treat real situations [10, 11]. An alternative consisting in establishing an empirical correction procedure has been explored for several years [8, 9, 11]. Recently, such an approach led to the introduction of a mathematical correction-factor for each diode and whose role is to correct the light energy it collects [11]. In the present work, the development of this mathematical model is generalized and its ability to be used to correct multiple-scattering effects in a given situation is investigated.

### Presentation of the model

In this section the empirical model of multiple scattering correction proposed by [11] is presented and generalized. A series of correction factors  $\tilde{\kappa}_i(T)$  is introduced to correct from multiple-scattering effects the scattering-signal collected by each diode  $i$ . The correction factors  $\tilde{\kappa}_i(T)$  are given by:

$$\tilde{I}_i(T) = \frac{I_i(T)}{\kappa_i(T)} \quad (1)$$

where  $I_i(T)$  is the normalized measured scattering-signal distribution and  $\tilde{I}_i(T)$  is the scattered signal distribution free of any multiple-scattering effects. The model assumes that the correction factors are functions of the transmission  $T$  only. (The transmission is the ratio of the undiffracted light intensity  $I$  to the incident light intensity  $I_0$ , i.e.,  $T = I/I_0$ ). The determination of the correction factors  $\tilde{\kappa}_i(T)$  is performed on the basis of the coefficient series  $\kappa_i(T)$  defined by:

$$\kappa_i(T) = \frac{I_i(T)}{I_i(T')} \quad (2)$$

where  $I_i(T)$  is the normalized scattered-signal collected by diode  $i$  during the measurement of a spray whose length is equal to  $L$ , and  $I_i(T')$  is the normalized scattered-signal collected by diode  $i$  during the measurement of *the same* spray but whose length is equal to  $L/N$ . If both measurements are free of any multiple-scattering effects, the normalized scattered-signal distributions  $I_i(T)$  and  $I_i(T')$  are identical and the coefficients  $\kappa_i(T)$  are equal to 1. Otherwise,  $\kappa_i(T) \neq 1$ . Using the Beer-Lambert law it is easy to show that:

$$T' = T^{1/N} \quad (3)$$

Equation (3) points out that  $T' > T$ , i.e., there is a range of transmission for which the  $L$ -spray measurement is affected by multiple scattering whereas the  $L/N$ -spray measurement is not. According to [11], the coefficients  $\kappa_i(T)$  are modeled by:

$$\kappa_i(T) = a_i - (a_i - \kappa_i(0))e^{-\gamma_i T} \quad (4)$$

where the three parameters  $a_i$ ,  $\kappa_i(0)$  and  $\gamma_i$  have to be determined. These parameters are such that:

$$\lim_{T \rightarrow 1} \kappa_i(T) = a_i \quad (5)$$

The case  $a_i = 1$  corresponds to a  $L$ -spray measurement identical to the  $L/N$ -spray measurement and the case  $a_i \neq 1$  denotes a difference between these two measurements that is imputable to the experiments. (For instance, it could be due to the presence of vignetting effect during the  $L$ -spray measurements.) Thus, the parameter  $a_i$  in Eq. (4) allows us to correct the  $L$ -spray measurements when necessary. This implicitly means that the  $L/N$ -spray measurement is assumed better than the  $L$ -spray measurement and that the  $L/N$ -spray measurement should never be corrected by the parameter  $a_i$ .

A multi-order correction process is applied to express the correction factors  $\tilde{\kappa}_i(T)$  (Eq. (1)) as a function of the coefficients  $\kappa_i(T)$  (Eqs. (2) and (4)). This process is a generalization of the second order correction approach suggested in [8, 9]. The multi-order correction process leads to:

$$\tilde{\kappa}_i(T) = a_i \prod_{j=0}^n \frac{\kappa_i(T^{1/N^j})}{a_i} \quad (6)$$

The correction factor series given by Eq. (6) are those to correct the  $L$ -spray measurements. Considering that the  $L/N$ -spray measurements should never be corrected by  $a_i$ , the correction-factor series appropriate for these measurements is:

$$\tilde{\kappa}_i(T') = \prod_{j=0}^{n-1} \frac{\kappa_i(T'^{1/N^j})}{a_i} \quad (7)$$

The correction-factor series expressions (Eqs. (6) and (7)) appear as the product of several terms. Note that when the index  $j$  increases, the coefficients  $\kappa_i(T'^{1/N^j})$  reach the asymptotic value  $a_i$ . Thus, if  $n$  is chosen great enough, the correction factors converge since the terms of the series tend toward 1. This last remark points out that this correction process can be applied even if the transmission is so great that no multiple-scattering effect is suspected. In this case,  $\tilde{\kappa}_i(T) = a_i$  and  $\tilde{\kappa}_i(T') = 1$ .

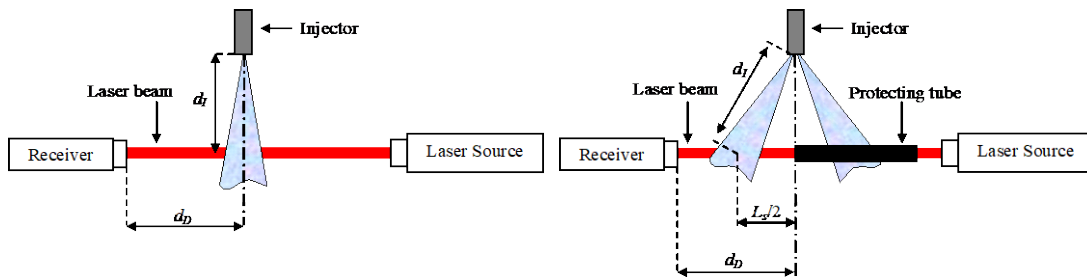
### Experimental investigation

The objective of the experimental investigation is to measure spray drop-size distribution with a Laser Diffraction Technique diagnostic and to correct the multiple-scattering effects that might appear as the injection pressure increases. The liquid (ShellSol D40: density = 766 kg/m<sup>3</sup>; surface tension = 25 mN/m, dynamic viscosity = 0.92 10<sup>-3</sup> kg/ms; vapour pressure = 0.30 kPa) is kept in a reservoir where its temperature is measured and maintained at 18°C by a heat exchanger. At the exit of the reservoir the liquid is filtered. A combination of a low pressure and a high-pressure pump provides an injection pressure ranging from 0.1 MPa and 12 MPa. This injection pressure is regulated and measured just above the injector.

The Laser-Diffraction equipment used to measure the spray drop-diameter distributions is the Spraytec 2007 from Malvern. This diagnostic has been specifically conceived to investigate highly transient dense sprays. The wavelength and diameter of the laser beam are 632.8 nm and 10 mm, respectively. A series of 36 diodes equips the receiver. The collecting lens has a focal length equal to 300 mm and the corresponding measurable diameter range is 0.1-900 μm. The measurements are performed at the greatest available acquisition rate, i.e., 10 kHz and the centre of the optical probe is located at 60 mm which is the greatest distance at which the all spray can be measured, i.e., the width of the spray is equal to the laser beam diameter.

The injector used throughout the investigation is a high injection pressure device with three identical cylindrical discharge orifices. Each of them makes an angle of 42° with the injector axis allowing each jet to be independently investigated. This injector produces transient injections whose characteristics are imposed by an engine control unit and are kept constant throughout the investigation: injection time = 10 ms; injection frequency = 1 Hz. In this study, the injector behaviour during the stationary fully open-stage is considered only. The size distribution of the drops produced during the injector fully-open stage is obtained as follow.

Measurements are performed during 20 consecutive injections. For each injection, the transmission decreases with time, reaches a plateau and then increases. The plateau corresponds to the time interval during which the spray-body produced during the stationary fully open-stage of the injector goes through the laser beam. The distributions measured during this time interval are averaged and the resulting time averaged distributions are averaged over the 20 injections. Thus, the drop-size distributions presented hereafter are averaged on several injections as well as in time.



**Figure 1.** Malvern Spraytec arrangement – Left: one-jet measurement configuration; Right: two-jet measurement configuration (with protecting tube for the narrow-spray measurement)

Before investigating the influence and correction of multiple-scattering effects on the spray drop-size distribution, the performances in terms of flow rate and spray drop-size distribution of the three jets issuing from the injector must be compared. First, the flow rate during the fully-open stage is measured for each jet. We found that this flow rate is the same for the three jets and that the discharge coefficient of each jet is equal to 0.45. Second, the drop-size distribution of the spray produced by each jet must be compared. To achieve this, the injector is orientated such that one jet goes through the optical probe of the particle-sizer only (see Fig. 1-Left). The distance  $d_D$  between the spray centre and the receiver is equal to 175 mm. (We checked that this distance is small enough to avoid vignetting effects.) For each jet, the measurements reported a bi-modal drop-size distribution with one peak located in the small diameter range (less than 100 μm) and a second peak located in the large drop

population (between 100 and 500  $\mu\text{m}$ ). Considering the range of injection pressure and the diameter of the injector discharge orifice, this second peak appears unrealistic and reveals the presence of a few badly atomized liquid fragments. Spray visualisations in the region of drop-size distribution measurement confirmed this point. However, the first peak corresponds to the spray that we want investigate. In order to consider this spray only, we exclude from the analysis the light energy distribution collected by the 11 first internal diodes. Furthermore, to make sure that no vignetting effects appears at high injection pressure, we also exclude the signal collected by the external diodes 33 to 36. Experimental preliminary tests similar to those conducted by [11] helped to make this choice. Using these precautions, we found that the three jets issuing from the injector produce the same spray drop-size distribution.

### Empirical correction protocol: application, results and analysis

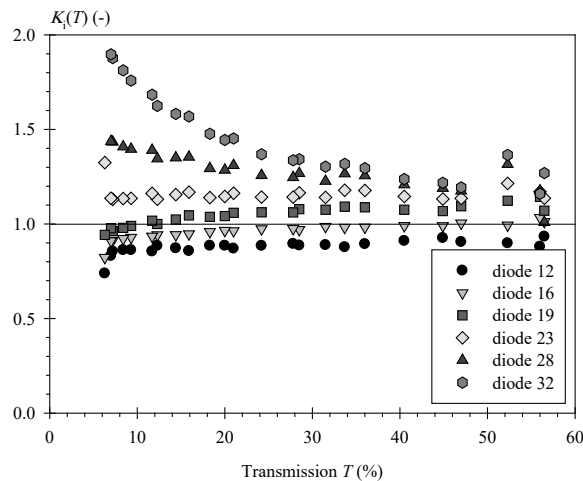
To illustrate the influence of the multiple-scattering effect as the injection pressure increases, a series of drop-size distribution measurements using the arrangement shown in Fig. 1-Right is performed. The injector is now orientated in order that two jets go through the optical probe. For each injection pressure, one measurement is performed with the two jets and one measurement is performed on the left jet only using a protecting tube shown in Fig. 1 – Right. The first measurement is referred hereafter as the large-spray measurement and is associated to the transmission  $T$ . The second measurement is referred hereafter as the narrow-spray measurement and is associated to the transmission  $T'$ . For each measurement, the scattering signal distribution is normalized: if  $Sc_i(T)$  designates the measured scattering signal distribution, the corresponding normalized distribution  $I_i(T)$  is given by:

$$I_i(T) = \frac{Sc_i(T)}{\sum_{i=12}^{32} Sc_i(T)} \quad (8)$$

The normalized distributions  $I_i(T)$  and  $I_i(T')$  measured as a function of the injection pressure, i.e., as a function of the transmission  $T$ , for the large-spray and narrow-spray measurements respectively allow the coefficients  $\kappa_i(T)$  introduced by Eq. (2) to be calculated. Figure 2 shows these coefficients for a selection of diodes.

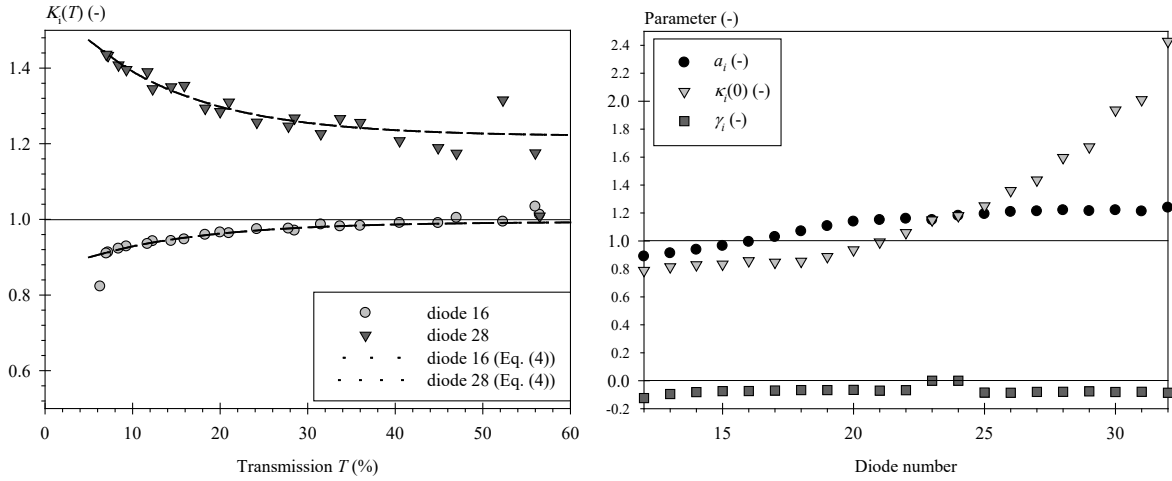
The behaviour reported in this figure is representative of multiple-scattering effects. They take place when the transmission decreases and are characterized by a decrease of the signal collected by the internal diodes ( $\kappa_i(T) < 1$  for  $i < 23$ ) and by an increase of the signal collected by the internal diodes ( $\kappa_i(T) > 1$  for  $i < 23$ ). Furthermore, as reported by many previous investigations ([7] for instance), multiple-scattering effects appear first on the small drop-population (external diodes) and diffuses in the big-drop population (internal diodes) as the injection pressure increases, i.e., as the transmission decreases.

An important point to be noted in Fig. 2 is that, although the coefficients  $\kappa_i(T)$  converge toward an asymptotic value when the transmission increases, this asymptotic value might be different than 1. This is mainly observed for the coefficients related to the external diodes. We must add here that performing large-spray measurements was rather tricky and very sensitive of the injector orientation. We believe that this experimental difficulty is at the origin of the behaviour observed in Fig. 2 for high transmissions.

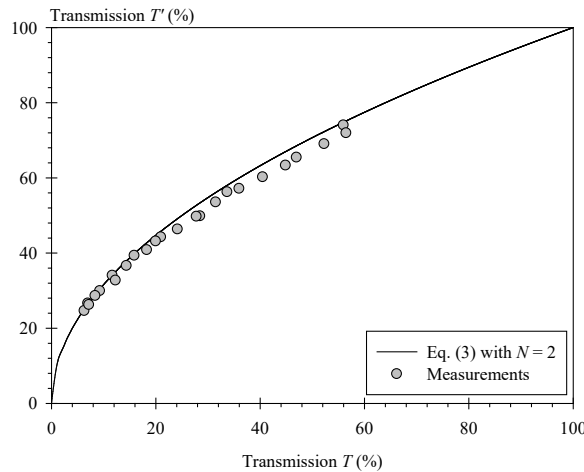


**Figure 2.** Evolution of the coefficients  $\kappa_i(T)$  for selected diodes

At this stage of the investigation, the question to be addressed is whether the coefficient  $\kappa_i(T)$  measured in this study can be modeled by the same mathematical expression as the one reported by [11]. This mathematical expression is the one given by Eq. (4). By considering this expression and the experimental behaviour reported in Fig. 2 it is easy to show that the parameter  $\gamma_i$  must always be negative and that the internal and external diode behaviour dissociates by the value of the ratio  $\kappa_i(0)/a_i$ : it is less than 1 for internal diodes and greater than 1 for external diodes. By respecting these observations, we found that the mathematical expression given by Eq. (4) was very much appropriate to reproduce the measured coefficients  $\kappa_i(T)$ . An example of comparison is presented in Fig. 3-left. We note a good agreement between the measurements and the mathematical expression given by Eq. (4). Figure 3-Right summarizes the values of the parameters found for each diode. The results presented in Fig. 3 show that the model established in a previous investigation is still appropriate here.



**Figure 3.** Left: Modelisation of the coefficient  $\kappa_i(T)$  with Eq. (4) for two diodes; Right: Parameters  $a_i$ ,  $\kappa_i(0)$  and  $\gamma_i$  for each diode

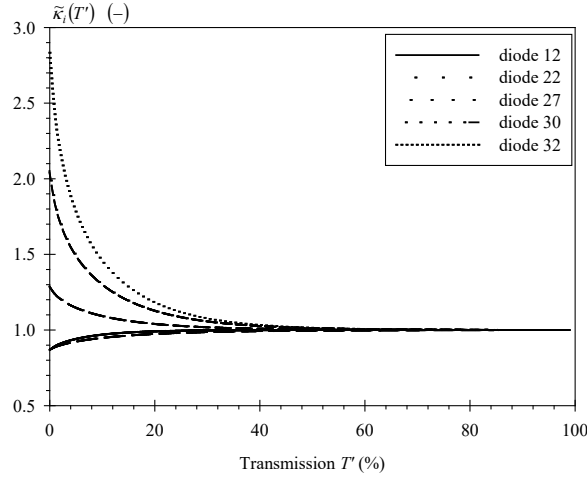


**Figure 4.** Comparison between large- and narrow-spray transmissions ( $T$  and  $T'$  respectively). Measurements and theoretical behaviour

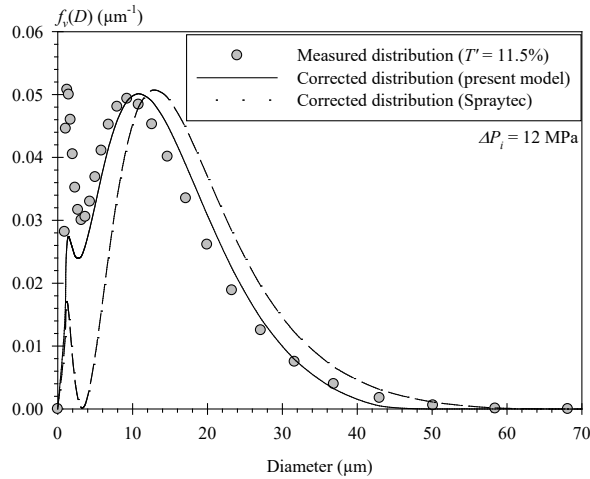
The analytical expression found for the coefficient  $\kappa_i(T)$  can be used to calculate the correction factor series given by Eqs. (6) and (7), which requires the estimation of the parameter  $N$ . This parameter is introduced by Eq. (3). As explained in the previous section, each jet issuing from the injector delivers the same flow rate and produces the same spray as far as the drop-size distribution is concerned. Therefore, the parameter  $N$  is likely equal to 2. This is confirmed in Fig. 4 that shows the evolution transmission  $T'$  with the transmission  $T$  and the theoret-

ical behaviour described by Eq. (3) with  $N = 2$ . We note good agreement between the measurements and the theoretical expectation.

Using the mathematical expression for  $\kappa_i(T)$  and  $N = 2$  allows the correction factor series (Eqs. (6) and (7)) to be calculated. As an illustration, Fig. 5 shows the correction factor series  $\tilde{\kappa}_i(T')$ . As explained in the section dedicated to the presentation of the model, this series corrects narrow-spray measurements only.



**Figure 5.** Correction factor series  $\tilde{\kappa}_i(T')$  as a function of the narrow-spray measurement transmission  $T'$

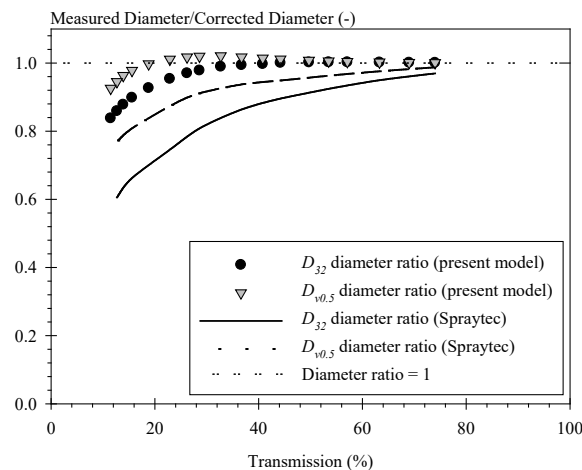


**Figure 6.** Comparison between the measured volume-based drop-size distribution and the distributions corrected by the present model and by the Spraytec multiple-scattering algorithm ( $\Delta P_i = 12$  MPa, narrow spray,  $T' = 11.5\%$ )

The interesting behaviour shown in Fig. 5 is that the correction factors become different from 1 when the transmission is less than 40-50%. This result agrees with the experimental and theoretical investigations that addressed the question of multiple-scattering effects on laser-diffraction size-distribution measurements.

Figure 6 shows the application of the present correction model on the narrow-spray measurement performed at the greatest possible injection pressure ( $\Delta P_i = 12$  MPa). We see that the application of the present correction model shows the expected behaviour since the volume-fraction represented by the small droplets is reduced. (As explained above, it is known that multiple-scattering in LDT measurement overestimates the small drop populations.) Note however, the tail of the distribution (in the large drop interval) is affected by the correction process in a way that is not the one expected. This behaviour has not been fully understood but we believe that it is due to the approximate determination of the tail of the distribution due to the presence of big non-atomized liquid fragments in the measuring volume that we tried to exclude from the analysis by ignoring some internal diodes.

We note also in Fig. 6 that the correction performed by the Spraytec algorithm is more important than the one due to the present model. A similar behaviour was found in another situation [11]. It is difficult to know which correction is the best but the examination of the characteristic diameters of the distributions may bring some interesting information on this very point. Indeed, the experimental investigation conducted by Paloposki and Kankkunen [7] demonstrated that the transmission at which a characteristic distribution-diameter reduces because of multiple-scattering effects depends on the characteristic-diameter type. For instance, they evidenced that the  $D_{v0.5}$  (50% of the volume of liquid is contained in drops with a smaller diameter than  $D_{v0.5}$ ) is affected by multiple scattering when the transmission is less than 30%. We calculated ratios of measured characteristic-diameters on corrected characteristic-diameters as a function of the transmission using either the present model or the Spraytec correction algorithm to perform the correction. Some of the results are shown in Fig. 7 for the mean diameter  $D_{32}$  and the representative diameter  $D_{v0.5}$ . We note that the results reported by the present correction model agree best with Paloposki and Kankkunen's observations than the Spraytec correction algorithm that provides a much greater correction.



**Figure 7.** Comparison of the characteristic diameters ratio versus the transmission (present model and Spraytec correction algorithm)

## Conclusion

The work reported in this article concerns the problem of laser-diffraction spray drop-diameter distribution measurements in the presence of multiple-scattering effects and addresses the question of an empirical protocol allowing drop-diameter distributions infected by multiple-scattering effects to be corrected. Such a protocol has been established in a previous investigation [11]. Considering the deviation of the scattered-signal collected by each diode as a function of the transmission of the measurement, this protocol succeeded in providing analytical correction factors to correct the scattered-signal distribution. A generalized mathematical description of this model is provided in the present article and the question the applicability of this model to other situations is addressed by considering other working conditions. It is found that the high injection pressure multi-jet injector investigated in this work accepts a similar multiple-scattering correction-model. This model assigns a correction factor to each diode whose role is to correct the light energy collected by this diode. Each correction factor introduces three-parameters that are functions of the diodes as well as on the operating conditions, i.e., injector, liquid, distance from injector. This last point is crucial since the present empirical model is based on the very restrictive assumption that light multiple-scattering effect depends on transmission only. Despite this and in agreement with many previous investigations, it reports that multiple scattering effects become non-negligible when the transmission is less than a limit of the order of 40 %-50 %. It is difficult to know whether the present model works better than the optional algorithm of the diagnostic. Considering the influence of multiple-scattering on characteristic distribution-diameters, it seems that the instrument correction algorithm performs over-corrections.

## Nomenclature

$a_i, \gamma_i, \kappa_i(0)$	parameters of the model [-]
$D$	Drop diameter [ $\mu\text{m}$ ]

$D_{v0.5}, D_{32}$	Characteristic drop diameters [ $\mu\text{m}$ ]
$f_v(D)$	Volume-based drop-diameter distribution [ $1/\mu\text{m}$ ]
$I_i(T)$	Measured normalized light energy distribution [-]
$\tilde{I}_i(T)$	Corrected normalized light energy distribution [-]
$Sc_i(T)$	Measured light energy distribution [a.u.]
$T, T'$	Large-spray and narrow-spray measurement transmission [-]
$\Delta P_i$	Injection pressure (MPa)
$\kappa_i(T)$	Empirical coefficient series (Eq.(2)) [-]
$\tilde{\kappa}_i(T)$	Correction-factor series (Eq.(1)) [-]

## Subscripts

$i$  Diode number

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