Image Statistical Analysis Procedures for Spray Morphology Investigation

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Abstract

A methodology of image statistical analysis to investigate spray shadowgrams is presented. Due to the peculiar morphology of the images of jets in crossflow a purposely-defined criterion for proper binarization is proposed. Such methodology is applied to an extensive set of sprays shadowgrams, obtained by crossflow injection. Jet leading edge and centerline could be determined using the proposed procedure, along with the progressive divergence of the two curves, representing the spray aperture angle. Results indicate that the ruling parameter for liquid placement and dispersion is the momentum flux ratio, with further influence of nozzle diameter and surface tension.

Introduction

One of the simplest and most used diagnostic systems for sprays is, out of doubt, flash shadowgraph. The diagnostic technique based on the principle of flash shadowgraph provides images in which a value on a brightness level scale is associated to each pixel. This value accounts for the amount of light, emitted by the source and crossing the spray. As a consequence of diffusion and absorption phenomena taking place in correspondence of the liquid-gas interface of the spray droplets, light attenuation occurs and the digital camera receives a damped signal. Light signal attenuation not only depends on real and imaginary part of the refraction index, but it gets stronger as droplet size and concentration increase. The overall amount of liquid-gas interface intercepted from source to detector contributes to light extinction, therefore it is not possible to get information about individual droplets.

In this paper the chance to achieve quantitative insight of a dense spray from shadowgraphic images (or shadowgrams), collected by simple, affordable diagnostic setup, is investigated. Since the usually available acquisition rates are orders of magnitude lower than the estimated characteristic frequencies of the surface instability involved in atomization processes, direct temporal tracking of jet dynamics is not pursued in this paper, and so a statistical approach is adopted. For each test condition the collection of statistically significant samples and the implementation of purposefully developed image statistical analysis techniques provide information on spray morphological features, namely liquid placement and dispersion.

The image elaboration routines have been tested with an extensive set of spray shadowgrams obtained by injecting liquid by plain nozzle placed on the sidewall of a premixing channel conveying high-density airflow. The tailoring of such statistical analysis to the crossflow atomization process results in the chance to capture some important features of the deflected spray, such as placement and shape of its leading edge [1] and centerline, from which derive the definition of spray angle as a tool to evaluate the level of liquid dispersion in the airflow.

Experimental and diagnostic setup

Image statistical analysis presented in this paper is primarily meant for flash shadowgraph of sprays. Test and further improvement of the elaboration routines were performed by exploiting a database of about 300.000 shadowgrams, collected in an optically accessible squared channel where a liquid jet is injected normally to high-density air crossflow.

Devices used for shadowgraph are a Xenon flash lamp with 15 µs pulse length, a Pulnix TM-6710 digital camera, set up to acquire 8-bit 640x200 pixel frames at 240 Hz, and a BNC delay generator for time base generation and synchronization. For each test condition a set of 1000 frames was collected. The experimental apparatus used in the preparation of this paper was aimed to reproduce the working conditions occurring in the premixing duct of an LPP gas turbine. The optically accessible channel with 25x25 mm2 cross-section conveys the compressed and pre-heated airflow. One of the sidewalls houses a plain orifice injector. Two injectors are used, with 0.3 and 0.5 mm outlet diameter. Injected liquids are distilled water and kerosene. Both liquid and gas velocity roughly range between 10 and 60 m/s. Air pressure is varied from 1.0 to 2.0 MPa, while air temperature ranges between 300 and 600 K. More details of the experimental facility and test conditions are available in [2]. For each test case liquid (kerosene, K, or water, W), injector (3 or 5 tenths of mm), air temperature (ambient temperature, F, or 600 K temperature, C) and pressure are selected, so that the conditions included in a test case differ from each other only in liquid and gas velocity. For instance the string "K3C20" indicates the set of data obtained by injecting kerosene through 0.3 mm nozzle into 2.0 MPa 600 K

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airflow.

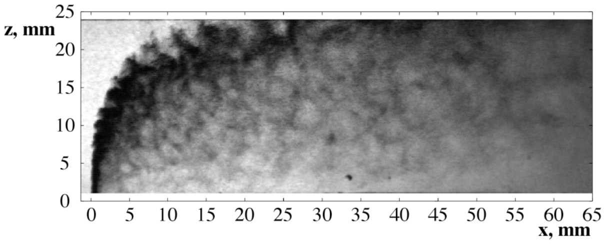

Fig. 1. Example of spray shadowgram. The spray is kerosene injected through 0.3 mm nozzle into 1.1 MPa 300 K airflow. Liquid velocity is 22 m/s. Air velocity is 21 m/s.

Binarization and averaging of the images

The first step for building up an analytical tool to describe the jet behavior is the definition of a consistent automated procedure to individuate the portion of the image pertaining to the jet plume, namely the “foreground” of the image. In general there is no standard way of isolating the pixel pertaining to the foreground from the other ones (background). In the case of an image where a clear distinction between the foreground and the background can be clearly individuated, the operation can be performed by using a filter (e.g. a gradient or a laplacian one) or more simply using a threshold operator [3]. In any case the choice of the operator to be used must take in account the characteristics of the images to be processed. In other words some assumption on the properties of the objects to be individuated is always required. These properties determine the choice of the proper threshold value to be used.

In the case here considered the situation is not simple and a preliminary analysis of image features is required to determine the best procedure to adopt for foreground determination. In figure 1 it is reported a typical example of a spray shadowgram. For this kind of images a simple threshold operation to discriminate between foreground (i.e. pixels assumed to pertain to the spray plume) and the background is made complex by the peculiar characteristics of this image. In fact, it can be observed that the luminosity gradient in the left part of the jet plume (i.e. the windward leading edge of the jet) is very clear and in this case a threshold operator could be applied to discriminate the edge of the spray plume with no serious concern about the choice of the threshold value. As regards the leeward (right) side of the jet there is no clear boundary between the jet plume and the background. In this case the choice of a threshold value can affect heavily the result. Reconstruct the trailing edge of the jet by binarization requires a more precise definition of the information content to be preserved.

Incidentally, in common practice the collected images are preliminarily processed by means of a cleanup operation, consisting of pixel-by-pixel subtraction of a reference image, collected in absence of the object of interest and usually referred to as background image. This operation results in improvement of the signal-to-noise ratio, even though the above-described characteristics of the image endure, as well as the need for a threshold selection criterion.

The application of a threshold operation to the N native images of a statistic ensemble, collected in a certain experimental condition, produces a set of N binary images. Native images are what the digital camera actually collects, and so they represent the field of intensity of light signal extinction. For each assigned threshold value a pixel of the binarized image is equal to 1 if light attenuation along the relative line of sight is higher than the threshold value. Averaging over the N frames gives each pixel a value ranging between zero (when either the light path is not intercepted by the spray or light undergoes attenuation lower than the assigned minimum threshold for all the images of the ensemble) and N (when light undergoes attenuation higher than the assigned minimum threshold for all the images of the ensemble). Since the spraying process is intrinsically stochastic, in the average binary image there is a number of pixels with a value intermediate between zero and N. This in-between value can be thought of as the probability that the spray intercepts the line-of-sight of a certain pixel. From this point of view the average binary image can be seen as a probability map of the occurrence of the spray.

It is evident that the average binary image depends heavily on the chosen threshold. It is thus necessary to find an objective criterion to define the optimum threshold value to be used in the binarization of the images.

Threshold criterion

The first step of the procedure require an analysis of the nature of the images in relation to the particular information content to be preserved in the binarization procedure. It has been already pointed out that the peculiarity of the images of liquid jets in crossflow is the existence of steep gradients on the spray leading edge and of much more progressive gradients on the leeward side.

The lack of detectable transition from the spray cloud to the background poses the problem of setting up some principles of meaningfulness of the segmentation, which would provide the basis for a threshold criterion. The principle here assumed is to pursuit the preservation of as much information as possible in the conversion from native to binary images. First of all the choice of the threshold value should account for possible discrepancies between different sets of images due to either lighting conditions or diagnostic settings. To achieve that, the threshold θ is defined as a percent share of the maximum extinction intensity, detected over the image.

The different interpretation of the average binary images with respect to native images suggests that they can provide a new insight into the spray, therefore the conversion from native to binary image, which intrinsically implies a loss of information, should retain information as much and as useful as possible. In lack of an applicable general principle for the threshold selection, the optimization of the average binary image can represent the basis to establish a target tailored threshold criterion. It is desirable to include most of the spray cloud into the foreground, that means setting a low threshold level on the light extinction intensity scale. On the other hand it is also advantageous to avoid the presence, in the spray core region, of a plateau of pixels with 100% occurrence probability. This plateau occurs when setting a low threshold, so that for a number of pixels the binary value is “1” in all the N images of the sample. The increase of the extent of such an area of uniformly probable pixels reduces the usefulness of the average binary image, so that from this point of view a higher threshold level would be preferable. The two guidelines so far described point to the choice of either the highest or the lowest threshold value. A suitable combination of them can result in an objective function to be optimized for the best threshold choice. This function has to account for the minimization of the number n_o of pixels with 100% occurrence probability. As regards the latter constrain, the maximization of the number $n_i - n_o$ of included but not saturated pixels is replaced by the minimization of its reciprocal, $1/(n_i - n_o)$. The two functions to minimize in dependence of θ are:

$$\begin{aligned} f_1(\theta) &= n_o \\ f_2(\theta) &= 1/(n_i - n_o) \end{aligned} \tag{1}$$

Since f_1 and f_2 have different range of values, it appears appropriate to normalize each to its own maximum before combining. The result is the objective function *F*:

$$F(\theta) = n_o/(n_o)_{MAX} + \left(\frac{1}{n_i - n_o}\right) \bigg/ \left(\frac{1}{n_i - n_o}\right)^{-1}_{MAX} \tag{2}$$

The function *F* is evaluated for about 260 experimental conditions, by setting the threshold as

$$\theta \in \{\ 10, 20, \ldots, 90\ \}\% \tag{3}$$

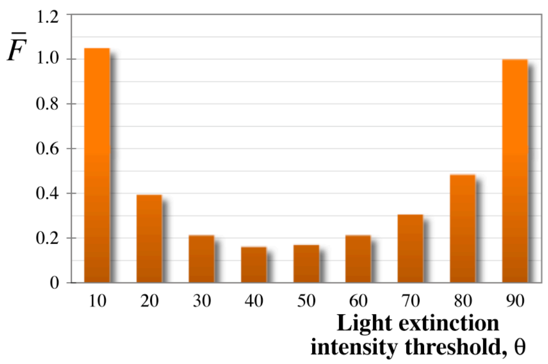

Fig. 2. Behavior of the average value of the objective function F *for discrete threshold values, calculated over the whole set of about 260 investigated conditions.*

For each experimental condition the dependence $F = F(\theta)$ results in a curve with a minimum. The overall behavior can be assessed by taking, for each threshold, the average of the target function calculated over the whole set of experimental condition. The result is reported in figure 2 and shows that the average of the objective function can be minimized by setting the threshold level between 40% and 50% of the maximum extinction intensity.

In the image analysis presented in the following the selected threshold value is the 50% of the maximum value of light extinction.

The spray centerline

The typical average binary image, reported in figure 3, is characterized by the zero-probability of the whole background, whereas in the spray zone the probability grows as one moves from the boundary to the centerline of the spray. In other words, supposing to move along a curvilinear coordinate following the spray propagation streamline, the plane normal to each point of the coordinate identifies a probability distribution. Given such a curvilinear coordinate following the spray stream, the whole average binary image can be reconstructed as a succession of probability profiles, and each of them can be replaced by a normal distribution to reduce the effect of noise. The locus of the medians of all the interpolating normal distributions along the curvilinear coordinate was defined as the *centerline* of the spray [4].

In figure 3 the leading edge (continuous line) and the centerline (dashed line) are superposed on the average binary image. The spray leading edge is evaluated as the average of the 1000 upwind boundaries of the binary images [2] and represents the liquid jet trajectory. On the contrary the spray centerline gives information on placement and evolution of the core of the liquid plume.

The spray angle in crossflow atomization

The availability of reference lines for both the boundary and the center of the spray suggests the chance to use them to investigate the characteristics of initial dispersion of the spray in the premixer.

The concept of angle of spray was introduced in the framework of liquid injected in quiescent or co-flowing air. In the case of diesel sprays [5], the spray angle is meant as a measure of the ability of the injector to disperse the liquid in the gas phase, and therefore it is to be maximized. In other cases the spray angle is a parameter to properly calibrate in order to match some requirements, as in the design of ordinary liquid-fuelled gas turbines, where the spray angle of swirl atomizers is chosen to place the fuel in correspondence of the airflow stagnation points for achieving a stable combustion [6]. In both plain-jet and swirl atomizers the spray angle is generally defined by referring to the initial slope of the conical boundary of the spray cloud. In the former case the spray angle is mainly governed by the liquid turbulence, affected by the characteristics of the internal flow and by the density ratio. As regards swirl atomizers the spray angle is ruled by the swirl chamber geometry, while increasing of the ambient gas pressure induces a stronger contraction of the spray [7].

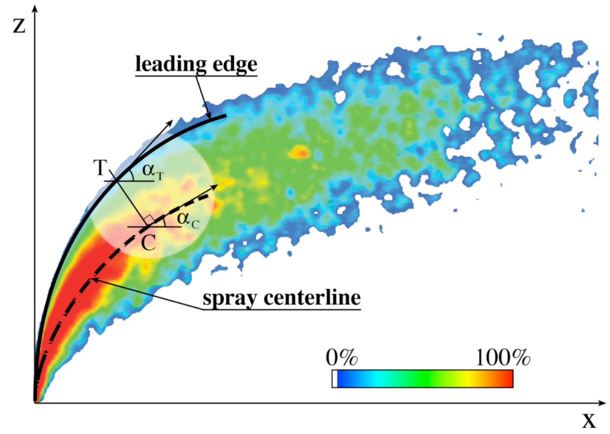

Fig. 3. Typical average binary image. The overlapped curves are the jet leading edge *(continuous line) and the* spray centerline *(dashed line).*

In the case of liquid injected in crossflowing airstream, the bending of the spray due to the airflow prevents the adoption of the same definition of spray angle. The definition proposed in this study is based on the above-introduced concept of centerline and aims to suggest a method to measure the level of primary dispersion of the liquid drops in the gas flow. By assuming leading edge and centerline as representative of spray boundary and core location, respectively the angle formed by these two lines can be considered a measure of the half-spreading of the deflected liquid plume. As in the other mentioned cases, the angle between the two curve lines is not constant as the spray evolves. The problem to spot a reference value of the spray angle is discussed in the next subsection.

Experimental evaluation of the spray angle

By assuming the centerline as corresponding to the injection axis of a jet in still air, the profile of the distance of the jet trajectory from the centerline is calculated and the average value of the slope of this profile is defined as spray angle. Obviously the same result is achieved by evaluating, for each point C of the centerline, the average difference between the angle α_C of the centerline, with respect to the x axis, and the angle α_T of the jet trajectory at the point T intercepted by the normal to the centerline in P (see figure 3).

The behavior depicted in figure 4 appears to be common to all cases. In conventional sprays is usual to consider the asymptotic initial value of the spray cone half-angle. In the present case this assumption is not viable, since the spray angle goes to zero by approaching the injection point, since leading edge and centerline share the initial vertical slope. As the spray evolves the angle increases up to a maximum value, after which it decreases with a milder slope. Both the mean and the maximum value of the spray angle were evaluated from experimental data. As regards the maximum, it was no possible to individuate a clear dependence on any parameter. On the contrary the data obtained for the average spray angles are presented in figure 5, plotted against the square root of the liquid-to air momentum flux ratio q, which in the performed experiments was varied between about *5* and *220*. The resulting values of spray angle range roughly between 5° and 50°. Although the points are quite scattered, the average spray angle shows an unmistakable trend to grow up as q increases. This seems to indicate that the achievement of a good level of dispersion of the liquid, at least as concerns the z axis, mainly depends on the capacity to provide enough kinetic energy to the liquid.

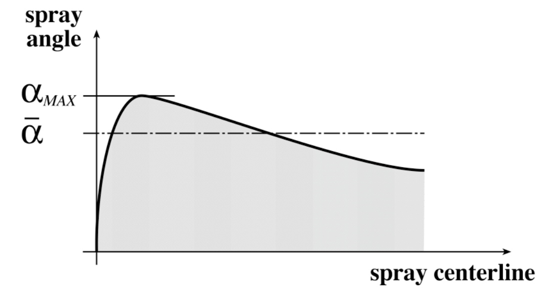

Fig. 4. General behavior of the spray angle as a function of the curvilinear coordinate (centerline). The maximum and average values are shown.

The qualitative observation of the relative placement of the experimental points, grouped by test case, suggests the chance to detect some further dependence. In particular two parameters expected to play a role and missing in the dependence on the momentum flux ratio pointed out so far, are the nozzle outlet diameter D and the liquid surface tension σ. The investigation of these two parameters is performed in parallel, therefore evaluating the effect of one of them by assuming an appropriate functional dependence for the other one. Figure 6 is similar to the plot in figure 5, but here the effect of nozzle diameter is investigated by grouping the experimental data in two categories, with either 0.3 or 0.5 mm diameter. In this case the parameter in abscissa is the square root of q, multiplied by a suitable function of the surface tension. The segmentation results successful, since the points with larger nozzle diameter place systematically above the other group. The reported trend-lines result from non-linear regression of experimental data. Their slope, which in log-scale denotes the exponent of power-law dependence, was found to be the same for both diameters, providing a value of best fitting exponent of the dimensionless diameter equal to 1.5.

The reciprocal procedure is presented in figure 7 for the surface tension. Also in this case point segregation is obtained by grouping as either water or kerosene data. It is noteworthy to remind that this grouping is purely illustrative, since in each group the surface tension further varies with temperature. The influence of surface tension is evident in the plot, even if less remarkable than nozzle diameter and resulting in a best fitting exponent of -0.25.

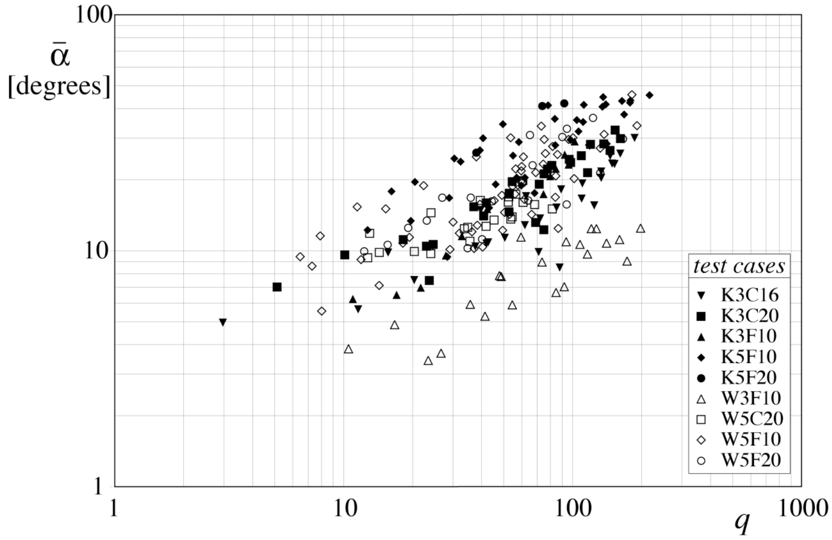

Fig. 5. Experimental data for the spray angle plotted as a function the momentum flux ratio q.

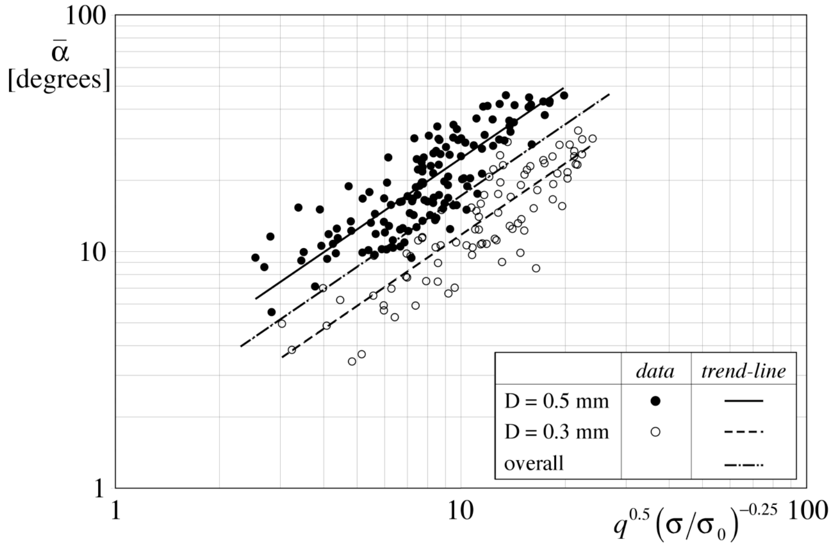

Fig. 6. Influence of nozzle diameter on the spray angle.

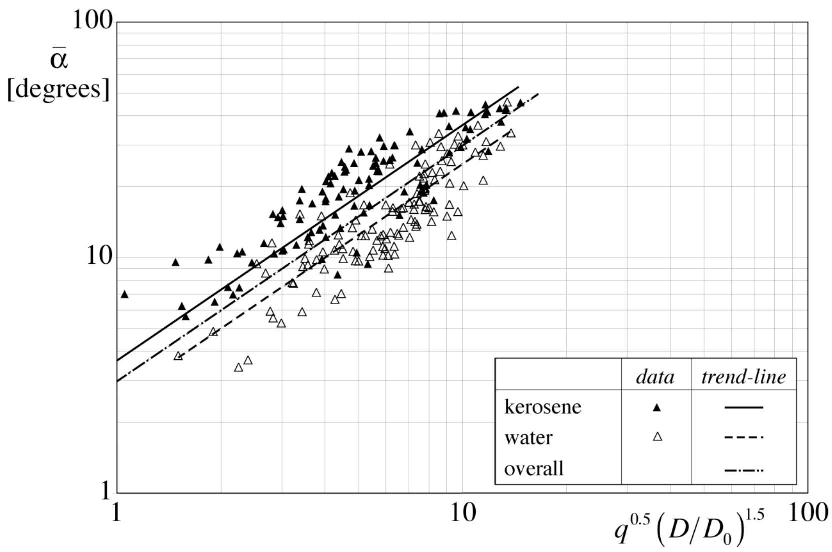

Fig. 7. Influence of liquid nature (namely surface tension) on the spray angle.

The empirical model which best fits the experimental measurements of the average spray angle is:

$$\bar{\alpha} = 2.49\ q^{0.5} \left(\frac{D}{D_0} \right)^{1.5} \left(\frac{\sigma}{\sigma_0} \right)^{-0.25} \tag{4}$$

The Pearson's linear correlation coefficient for this equation is found to be 0.868, and the good agreement with experimental data can be observed in figure 8. The model indicates that the dependence of liquid primary dispersion on q is slightly stronger than the dependence found for the liquid penetration [1]. From comparison with the empirical model of the leading edge also results that the spray angle has a stronger dependence on both injection diameter and surface tension. As a consequence the design of an atomization system based on crossflow injection can proceed by simultaneous optimization of energy allotment between phases and nozzle number and size. In addition the future expected resort to alternative fuels (such as synthetic kerosene) should consider the effect of surface tension on spray dispersion.

Conclusions

A new methodology of image statistical analysis, to study macroscopical features of a spray, was proposed. The paper demonstrated the feasibility of quantitative morphological investigation of a statistical sample of spray shadowgrams, collected by means of an affordable diagnostic system.

Image clean–up, averaging and binarization procedures were discussed and implemented. As regards the binarization process, a criterion for proper selection of the threshold level was formulated in terms of preservation of the maximum content of information embedded in average binary images. The proposed objective function resulted optimized for threshold level set to 50% of the maximum light extinction intensity. The elaboration of spray shadowgrams from crossflow injection system allowed for the definition of spray centerline, which can be used in combination with the leading edge of the spray to provide quantitative estimation, namely the spray angle, of the primary dispersion of the spray in the air crossflow. The results indicated that the ruling parameter for liquid placement and primary dispersion in the air crossflow is the liquid-to-air momentum flux ratio. Further dependence on injection diameter and liquid surface tension was pointed out.

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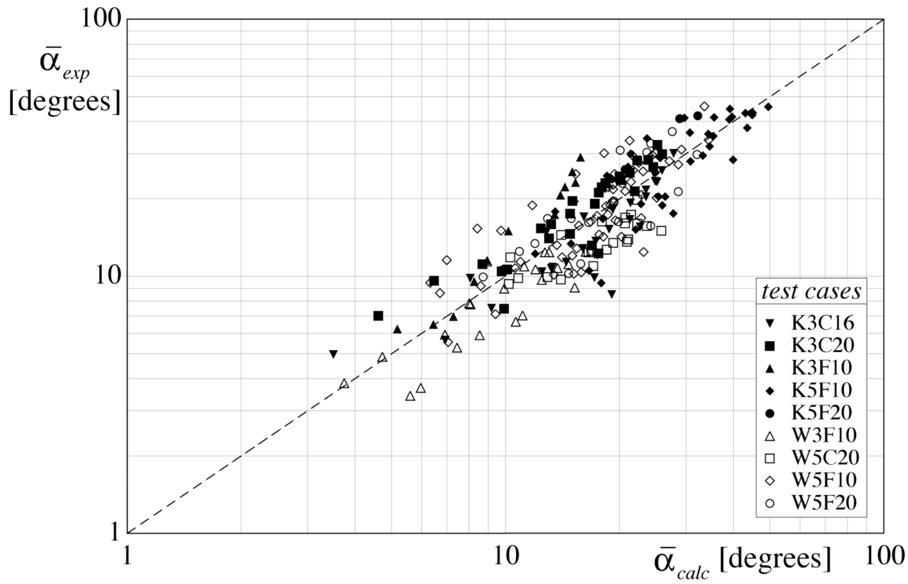

Fig. 8. Empirical model of the spray angle as a function of momentum flux ratio, nozzle diameter and surface tension.