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Liquid film break-up in a model of a prefilming airblast nozzle

I. S. Carvalho, M. V. Heitor

Abstract The paper describes the atomisation process of a liquid in an axissymmetric shear layer formed through the interaction of turbulent coaxial jets (respectively, inner and outer jets), with and without swirl, in a model airblast prefilming atomiser. The atomisation process and spray quality was studied using different visualisation techniques, namely laser shadowgraphy and digital image acquisition. The experiments were conducted for different liquid flow rates, Reynolds numbers ranging from 6600 to 66000 and 27300 to 92900 for the inner and outer air flows, respectively, for different outer flow swirl levels, and two liquid film thicknesses —0.2 and 0.7 mm. All the tests were carried out at atmospheric pressure and using water.

The results include the analysis of the film structure at break-up and of the break-up length, and suggest that the deterioration of the liquid film close to the atomising edge exhibits a periodic behaviour and is mainly dependent on the inner air velocity. Film thickness strongly affects the time and length scales of the break-up process for the lower range of air velocities. For higher inner air velocities, the break-up length and time become less dependent on liquid flow rate and initial film thickness.

1 Introduction

The quality of liquid atomisation, as indicated by the size distribution of the droplets produced by a given injector following liquid disintegration, has been used for a numbers of years to evaluate typical injection conditions and liquid properties (Weiss and Worsham 1959; Gretzinger and Marshall 1961; Kim and Marshall 1971; Rizkalla and Lefebvre 1975a, b; Lorenzetto and Lefebvre 1977; Rizk and Lefebvre 1980; El-Shanawany and Lefebvre 1980). Generally accepted findings are that the drop size increases with an increase in liquid viscosity and surface tension (Rizkalla and Lefebvre 1975a, b; Jasuja 1979; Rizk and Lefebvre 1980; Aigner and Wittig 1988; Beck et al. 1991), but decreases with increasing air/liquid mass ratio and air velocity (Lorenzetto and Lefebvre 1977; El-Shanawany and Lefebvre 1980; Rizk and Lefebvre 1980; Sattelmeyer and Wittig 1986; Beck et al. 1991). Even though atomisation has been used very extensively in a wide variety of applications, and empirical correlations of the mean drop size as a function of the operating parameters were obtained, the knowledge of the airblast atomisation process is still incomplete, mainly due to the lack of understanding and knowledge of the fundamental physical mechanisms of liquid break-up into drops, as recently discussed by Engelbert et al. (1995).

The dense spray region near the injector exit where the primary atomisation occurs has remained relatively inaccessible, leading to ambiguous conclusions concerning the liquid phase structure and the atomisation mechanisms in this region. The structure of the liquid phase in the near-injector region including the "liquid core length" and liquid phase geometries near the liquid core is not only significant in itself as a characterisation of the liquid-phase behaviour in this region, but also in relation to identification of the major dynamic mechanisms responsible for liquid core break-up (Yule and Filipovic 1992) and subsequent atomisation. The optimisation of the fuel injector design, performance as well as of the operating conditions in order to achieve good atomisation requires a detailed understanding of the process in the near-injector region. In addition, the liquid film break-up length is an important characteristic of the prefilming airblast atomisers (as the extent of the intact liquid core is for the pressure atomisers), and may contribute to an improved understanding of the atomisation in the near exit region and to liquid-air mixing characteristics. Also, there is an obvious interest to associate the dominant length scale of liquid surface disturbances and/or the liquid break-up length with some diameter of the observed droplets in the far field region.

This paper considers the break-up of an annular liquid sheet surrounded by inner and outer coaxial air streams, in a nozzle configuration which resembles those used in practical combustors, and follows the work reported by Carvalho and Heitor (1995). The main concern of the study is the detailed analysis of the near exit zone of a prefilming airblast atomiser. Previous work included laser Doppler measurements to characterise the mean and turbulent air velocity field in the absence of the liquid film (Carvalho and Heitor 1993, 1996; Carvalho 1995). Then, laser shadowgraphy and high speed video were used to analyse the characteristics of the liquid film, and

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the results used to determine the time and length scales of the break-up process. The main objective is to improve knowledge of the atomisation of liquid fuels in practical combustors by having a closer insight into the break-up mechanism of annular liquid films. The next section describes the flow configuration and the experimental techniques used throughout the work. Chapter 3 presents and discusses the results and the main findings are summarised in the last section.

2
Experimental method

2.1
Flow configuration

The model atomiser used throughout the work, shown in Fig. 1, consists of three coaxial cones, as follows: i) an inner cone with a 5° angle and an exit diameter of $D_i = 5$ mm; ii) an intermediate cone for water flow, which may provide an annular water film with a thickness of 0.2 or 0.7 mm; and, iii) a 70 mm long external cone with an angle of 35° and an exit

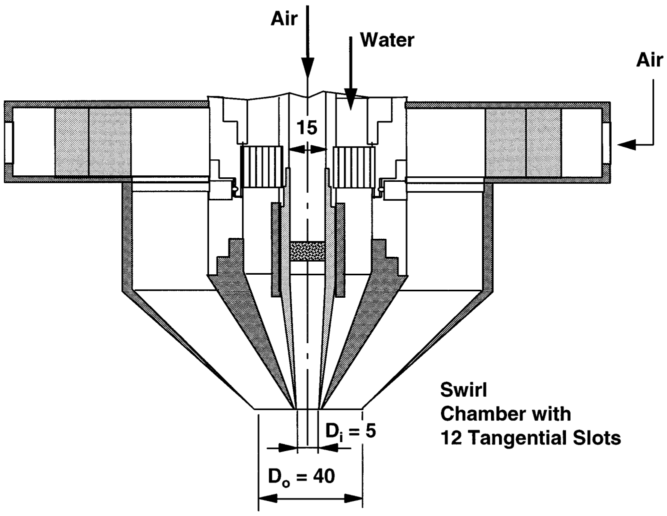

Fig. 1. Schematic diagram of flow configuration (dimensions in mm)

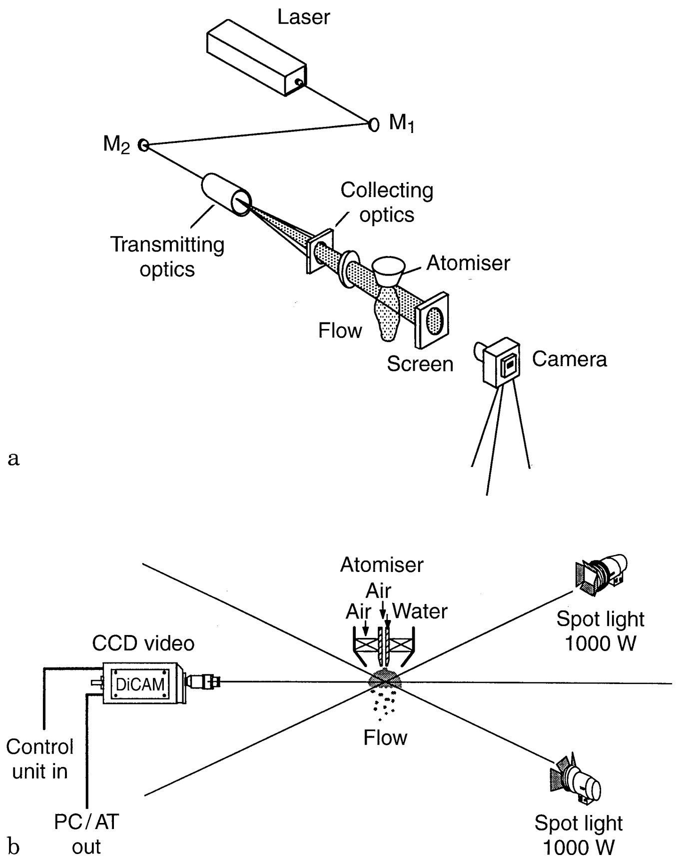

Fig. 2a, b. Configuration of the visualisation system **a** Shadowgraphy; **b** digital image acquisition

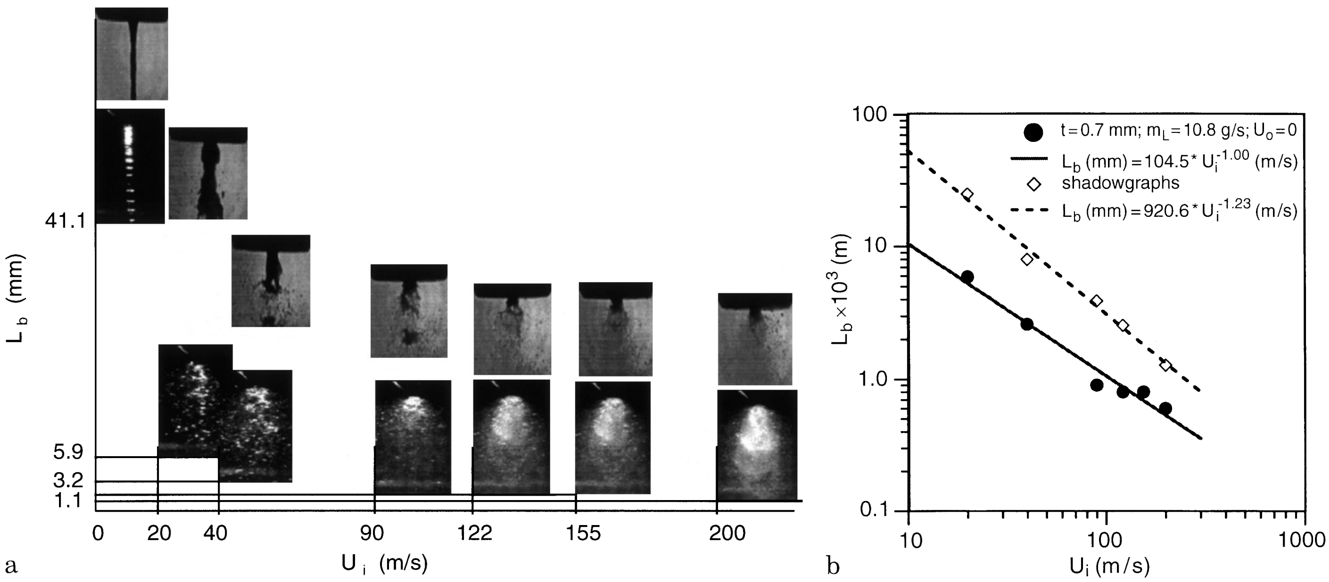

Fig. 3a, b. Influence of the inner air velocity, U_i, on the break-up length, L_b – single jets ($t = 0.7$ mm; $m_L = 10.8$ g/s; $U_o = 0$). **a** Visualisation results; **b** quantitative representation of the break-up length (values taken from sample visualisation results, as shown in Fig. 3a). ◇ shadowgraphy; ● ICCD camera diameter of $D_o = 40$ mm. Air is passed along either sides of the liquid film to produce a shear force at the air-liquid interface. Air can be fed through the inner and outer cones separately, with rotation imparted to the outer air flow by means of a swirl chamber that generates a tangential flow by the injection of air through 6 or 12 tangential slots. The inner and outer air streams were separately measured and the overall degree of swirl was characterised through a non-dimensional swirl number, S, and estimated from laser-Doppler velocimetry measurements obtained at the exit plane of the nozzle (Carvalho and Heitor 1996), in accordance with Beér and Chigier (1972). In the present study, a range of swirl levels of the outer air flow was analysed: $S \leqslant 2.5$.

Water was used as a test liquid, and the results reported here are for liquid mass flow rates of 5.8, 10.8 and 13.9 g/s and liquid film thicknesses of 0.2 and 0.7 mm. Experiments were conducted for inner air velocities up to $U_i = 200$ m/s ($Re_i = 66000$, defined as $Re_i = \rho U_i D_i / \mu$, where D_i is the inner jet diameter) and outer air velocities up to $U_o = 40$ m/s ($Re_o = 92900$, defined as $Re_o = \rho U_o D_h / \mu$, where D_h is the hydraulic diameter of the outer air annulus).

2.2 Experimental techniques

The analysis of the liquid film break-up downstream of the nozzle was performed, making use of two visualisation techniques: i) laser shadowgraphy was achieved by using one of the several conventional optical configurations (see e.g. Merzkirch 1974; Goldstein 1983). The system includes 2 mirrors (M_1 and M_2) and two lenses (L_1 and L_2) in order to produce a cylinder of parallel light (60 mm in diameter) that crossed the flow and project an image on a screen. A magnification factor of 1.5 was used. A 35 mm camera was used to register the flow images in 100 ASA films with exposure times of 125 ms; and, ii) back lighting of the flow was used with an ICCD camera with a minimum time exposure of 10 ns and 8-bit resolution. Image processing of the results enabled the recognition of certain geometrical characteristics of the sprays analysed, as well as a closer insight into the liquid film disintegration process.

A schematic diagram of the optical configuration is shown in Fig. 2, which presents the two visualisation techniques used for the analysis of the overall spray characteristics and for the near exit zone region in order to provide a better understanding of the liquid film disintegration mechanisms that precede droplet formation.

The main limitation of the shadowgraphy consisted on the averaging nature of the method, as well as on the minimum time exposure (125 ms) required in the present flow. For the image digitisation technique, a narrow focusing plane, adequate acquisition/electronic gain were used, in order to optimise S.N.R. and the accuracy of the measurements. Details on the camera performance and error analysis are reported in Carvalho (1995). In both methods the possibility of a statistical analysis of the collected data is obviously a time consuming approach, and is a severe limitation of the techniques when quantitative information is a primary goal. This is the case of the analysis of the break-up lengths, which have been determined from a large number of images. The results exhibited a standard deviation up to 25%, so that the values reported below may be associated with a statistical uncertainty of less than 20%.

3 Results and discussion

The description and analysis that follows is based on flow visualisation, and the results are presented either in a qualitat-

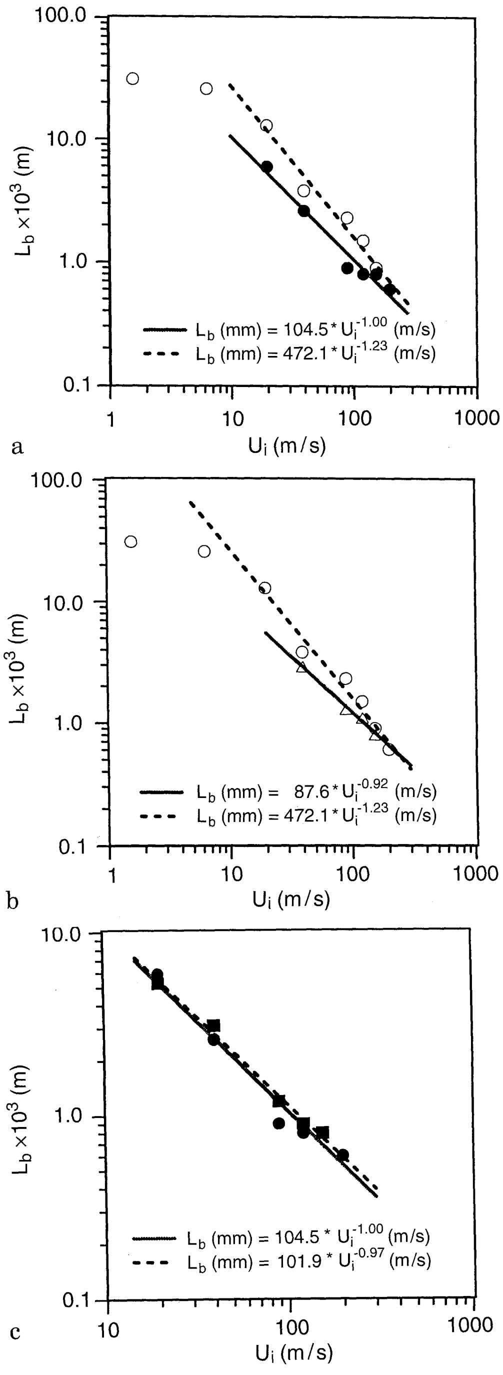

Fig. 4a–c. Influence of the inner air velocity on the break-up length for single jets ($U_o = 0$). **a** For $m_L = 10.8$ g/s and different liquid film thicknesses (○ $t = 0.2$; ● $t = 0.7$ mm); **b** for $t = 0.2$ mm and different liquid mass flow rates (△ $m_L = 5.8$ g/s; ○ $m_L = 10.8$ g/s); **c** for $t = 0.7$ mm and different liquid mass flow rates (● $m_L = 10.8$ g/s; ■ $m_L = 13.9$ g/s)

ive or quantitative form, for the analysis of the liquid film disintegration process, and for the determination of the liquid film break-up lengths. For purposes of clarification a reference flow was selected: single jet flow with a liquid film thickness $t=0.7$ mm and a liquid mass flow rate $m_L=10.8$ g/s. The discussion is structured in terms of the most important parameters: i) inner air velocity, U_i; ii) liquid film thickness, t, and mass flow rate, m_L; iii) outer air velocity, U_o; and, iv) outer air swirl level.

Figure 3 shows the results, obtained with both visualisation techniques, of the break-up length, L_b, as a function of the inner air velocity, U_i, for single jets, with $t=0.7$ mm, $m_L=10.8$ g/s and $U_o=0$. The results quantify the length from the nozzle tip to the point at which the liquid film fragments and show that as the primary air velocity increases, the break-up length decreases due to the rise of the aerodynamic force acting on the liquid film. The break-up length decreases with U_i to the power of −1.0, when the results from the ICCD camera are considered.

Figure 4a shows the results obtained for the liquid film break-up length for the single jet configurations with two different liquid film thicknesses (0.2 and 0.7 mm) and $m_L=10.8$ g/s. The break-up length increases with decreasing air velocities, and a substantial deterioration in the spray quality is obtained for reduced air velocities. It was observed that the threshold value of air velocity below which atomisation is of poor quality, is around $U_i=40$ m/s and further reduction in velocity results in lack of atomisation (see Fig. 3a). As the inner air velocity increases L_b decreases in a similar way for both liquid film thicknesses, although for a constant value of U_i the measured values of L_b are always smaller for $t=0.7$ mm. This difference becomes less significant for higher values of U_i, and for high enough inner air velocities L_b tends to become independent of t. For $t=0.2$ mm the break-up length decreases with U_i to the power of −1.23, while for $t=0.7$ mm, $L_b \propto U_i^{-1.0}$. It should be mentioned that the empirical correlations presented were calculated for $U_i \geqslant 20$ m/s, and do not include the measured values for lower inner air velocities. This is related to the atomisation process itself, and will be referred later on in this discussion.

Figures 4b and c present the break-up lengths for the single jets as a function of the inner air velocity for the two liquid film thicknesses and different liquid mass flow rates. As previously observed, there is a strong dependence of L_b with U_i and, for both liquid film thicknesses, it is clearly seen that for $U_i > 100$ m/s L_b tends to become independent of either t or m_L. Figure 5 shows shadowgraphs for the single jet configuration

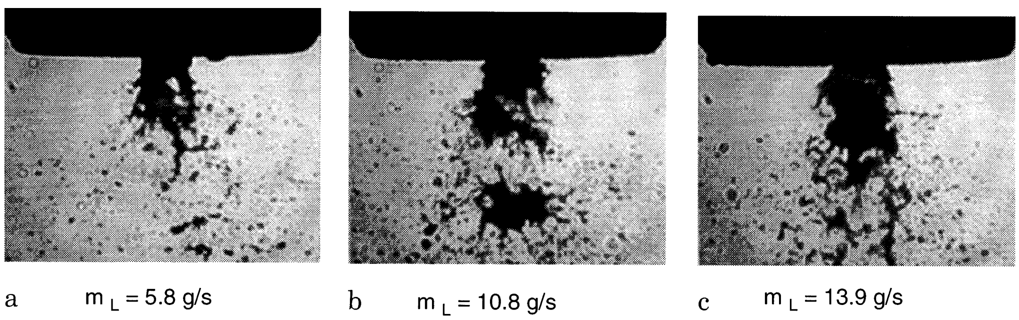

Fig. 5a–c. Shadowgraphs of the near nozzle exit region for the single jet configuration with $t=0.7$ mm and $U_i=90$ m/s ($U_o=0$). **a** $m_L=5.8$ g/s; **b** $m_L=10.8$ g/s; **c** $m_L=13.9$ g/s

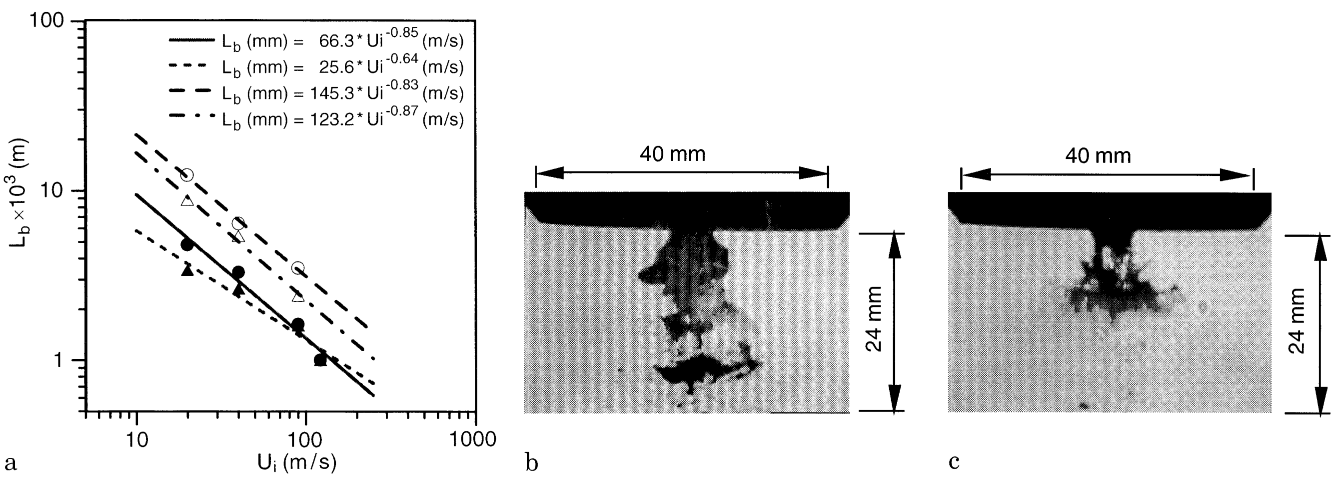

Fig. 6a, b. Influence of the inner air velocity on the break-up length for coaxial jets without swirl ($m_L=10.8$ g/s). **a** $t=0.2$ mm; ○ $U_o=20$ m/s; △ $U_o=40$ m/s; $t=0.7$ mm; ● $U_o=20$ m/s; ▲ $U_o=40$ m/s; **b** $t=0.7$ mm; $U_i=U_o=20$ m/s; **c** $t=0.7$ mm; $U_i=20$; $U_o=40$ m/s

($t = 0.7$ mm), with $U_i = 90$ m/s and for three different liquid mass flow rates. It is easily observed that the break-up length increases with m_L (as also suggested from results reported in Fig. 4). The results show that the deterioration of the liquid film close to the atomising edge of the nozzle is associated with a periodic process mainly dependent on the inner air velocity (see also Fig. 3a).

It is expected that in the disintegration of a liquid film into ligaments and drops, the observed mechanism will vary in accordance to the velocity and turbulence characteristics of the liquid film and with the velocity and mass flow rate of the atomising air, as well as with the way the atomising air impinges on the liquid film, as previously discussed by Lefebvre (1992). Figures 6–9 show the influence of these parameters on the break-up length, and lead to the conclusion that, for high enough values of the inner air velocity prompt atomisation is achieved (for all flow configurations), and the break-up length becomes independent of the liquid film thickness, as previously stated by Lefebvre (1992). Further details can be found in Carvalho (1995).

Figure 6 shows the corresponding results obtained for coaxial jets, for $t = 0.2$; 0.7 mm, $m_L = 10.8$ g/s and $U_o = 20$; 40 m/s. The coaxial non-swirling flows show similar trends to those reported for the single flows, i.e., the break-up length decreases with increasing inner air velocity, and the influence of an outer coaxial air flow is seen to be small when compared with the inner atomising air characteristics. For constant values of U_i the break-up length decreases for higher values of U_o, for both liquid film thicknesses. The smallest values of L_b were found for $U_o = 40$ m/s and $t = 0.7$ mm, corresponding to lower liquid velocities. Also, as observed for the single jet configuration, the break-up length tends to be independent of m_L and t, providing U_i is high enough. The influence of the outer air is easily seen from the shadowgraphs presented in Fig. 6b and 6c.

Figure 7 shows shadowgraphs of the near exit zone for the coaxial swirling jets with $t = 0.7$ mm, $m_L = 10.8$ g/s, $U_i = 20$; 122 m/s and different values of U_o (the swirl level increases from $U_o = 12$ m/s to $U_o = 36$ m/s). For higher values of U_i, the intact film length decreases near the nozzle exit, as well as the characteristic dimensions of the formed clusters and ligaments. Although for higher values of U_i (see Fig. 7b) it is difficult to establish the influence of the outer air swirl level on the break-up length, L_b decreases for increasing values of U_i and U_o, as observed in the previous cases. Similar correlations were also found for these flows (Carvalho, 1995), where $L_b \propto U_i^n$, with $-0.94 < n < 1.49$, but the difficulty in defining a break-up length due to the presence of a rotating air flow became clear, and no doubt a higher degree of uncertainty is associated with these measurements. Nevertheless, it is clearly seen that the flow spreading rate increases for higher swirl levels.

From the previous results, the break-up length of the liquid film was seen to be strongly dependent on the inner air velocity up to 90 m/s. However, when compared with the previous configurations, and for the same value of U_i, shorter break-up lengths are observed for an outer swirling flow. This is easily seen in Fig. 8, where the break-up length is plotted for different coaxial configurations with constant U_L and U_i, and the characteristics of the outer air flow are varied, thus allowing to observe the influence of a swirling and non-swirling outer air on L_b. For all the configurations L_b decreases with increasing Reynolds number of the outer flow, although this influence is particularly stronger for the swirling flows ($\partial L_b / \partial U_o = -0.96$) when compared with the coaxial non-swirling configurations ($\partial L_b / \partial U_o = -0.57$).

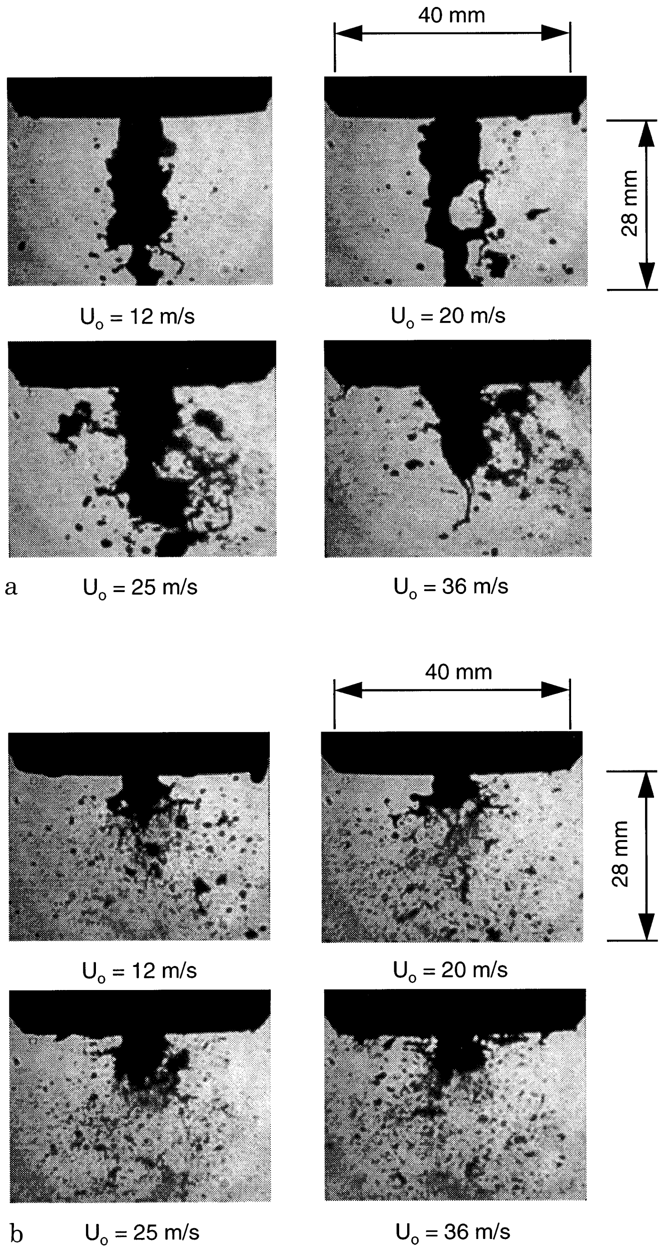

Fig. 7a, b. Shadowgraphs of the near nozzle exit region for coaxial swirling jets with $t = 0.7$ mm and $m_L = 10.8$ g/s; **a** $U_i = 20$ m/s; **b** $U_i = 122$ m/s

The results presented in Fig. 9 show that the break-up length increases with the liquid velocity or, as expected, L_b is dependent on the Reynolds number of the liquid film. This dependence tends to attenuate as the inner air velocity increases, and for $U_i \geqslant 155$ m/s the break-up length becomes quite independent of the velocity of the liquid sheet and, consequently, also independent of the liquid film thickness.

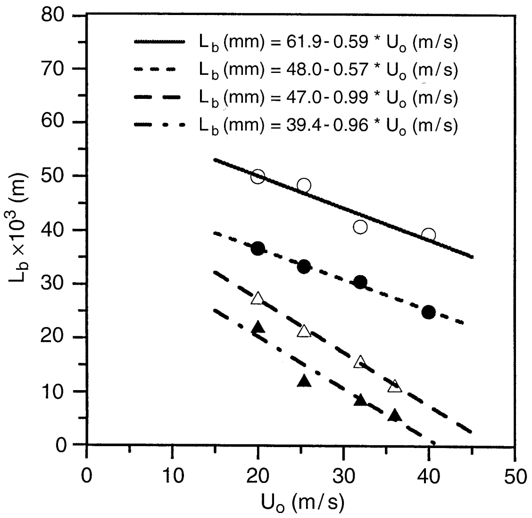

Fig. 8. Influence of the outer air flow characteristics on the break-up length for $t=0.7$ mm, $m_L=10.8$ g/s and $U_i=0$ without swirl: ○ $U_o=20$; ● $U_o=40$ m/s; with swirl: △ $U_o=20$; ▲ $U_o=36$ m/s

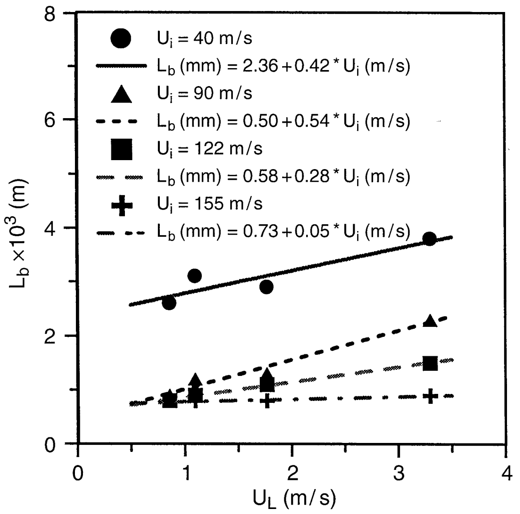

Fig. 9. Influence of the liquid velocity on the break-up length

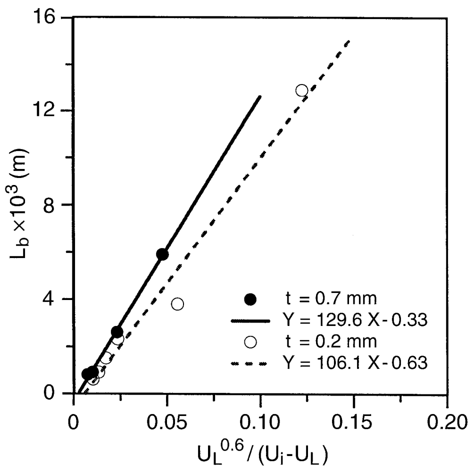

Fig. 10. Comparison with the correlation proposed by Arai and Hashimoto (1985)

Figure 10 presents a comparison between the present experimental results, obtained for the single jet configuration, with the correlation proposed by Arai and Hashimoto (1985). The results show a good agreement for $U_i \geqslant 20$ m/s, as for lower inner air velocities poor atomisation is achieved and the "atomisation regime" assumes different characteristics, as can be seen from the results presented in Fig. 4. The correlation coefficient between the best fit and the experimental data was 0.99 and 0.97 for $t=0.7$ and 0.2 mm, respectively.

From the analysis of the above mentioned configurations, several "atomisation regimes" were observed, namely: i) for $U_i=0$, the Rayleigh break-up is observed; ii) for $0<U_i<5$ m/s the break-up is characterised by bubble formation and deformation; iii) for $5<U_i<40$ m/s, L_b decreases rapidly as U_i rises and two types of break-up were found: the film/cluster/ligament type for relatively small air velocities, and the ligament/shattered drops type for higher air velocity; iv) for $40<U_i<120$ m/s, L_b decreases slowly as U_i increases; and v) for $U_i>120$ m/s, prompt atomisation is observed, and the break-up length continues to decrease very slowly with U_i, keeping a very low value, for the velocity range under analysis, and would theoretically (Dombrowski and Johns, 1963) approach zero for high enough values of U_i. Although this classification follows the observed behaviour of the single jet configurations, this description can be extended to the coaxial flow configurations excluding "regimes" i) and ii).

Since airblast atomisation relies upon the airstream momentum for liquid disintegration (Stapper et al. 1992; Zheng et al. 1996), the air-to-liquid mass ratio would clearly seem to be an important variable influencing the spray quality. Deficiency of air would result in failure to overcome the viscous/surface tension forces that are resisting liquid disintegration, while an "excess" of air may result in some of the air not actually participating in the liquid break-up, as previously suggested by Lefebvre (1992).

Figure 11 shows the previous results in a non-dimensional form, with accordance to the parameter which was found to control the break-up process for the different flow configurations: the air-to-liquid momentum ratio. For an easier comparison, the results are plotted together for all the flow configurations under analysis in Fig. 11b. The best fit, $\log(L_b/t^{1.3}) = 9.20 - 0.69 \log([U_i/U_{liq}]^2 + 0.1 * (U_o/U_{liq}]^{2.3})$, was obtained for an exponent of the liquid film thickness of 1.3, and when a constant $C=0.1$ was considered taking into account the reduced influence of the outer air flow conditions in the process of liquid film break-up. Once again, this correlation is valid for $U_i \geqslant 20$ m/s. It is easily observed that the inner air is more effective on promoting atomisation than the outer air. The use of outer swirling air influences the atomisation process, but the quality of the spray is strongly dependent on the inner air velocity U_i.

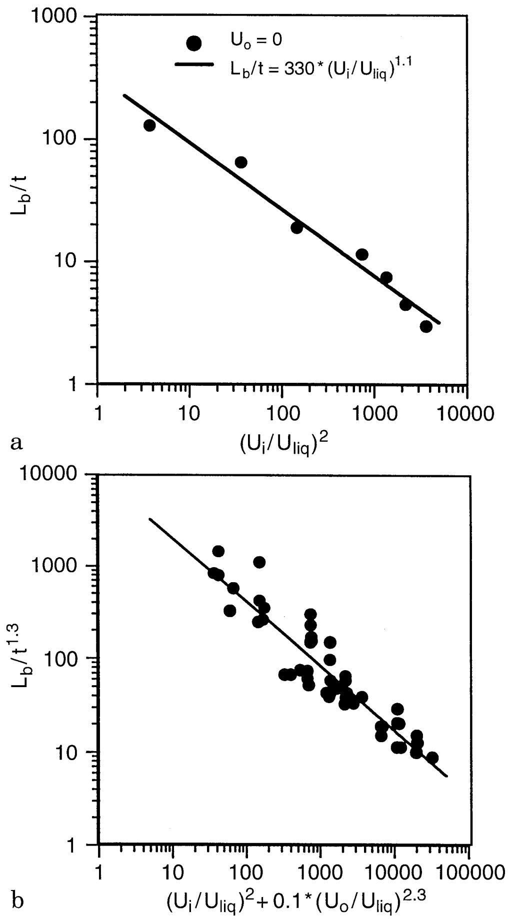

Fig. 11a, b. Influence of the $(U_i/U_{\rm liq})^2$ parameter on the break-up length for $t=0.2$ mm and $m_L=10.8$ g/s. **a** single jets ($U_o=0$); **b** single + coaxial + swirling flows

4 Conclusions

The process of liquid atomisation downstream of a prefilming airblast nozzle is reported making use of laser shadowgraphy and digital image acquisition. The analysis is directed towards a detailed investigation of the break-up of an annular liquid film in the presence of co-flowing air with and without swirl. The experiments were conducted in turbulent flows, for different liquid (water) mass flow rates, inner air velocity up to 200 m/s, and outer air velocity up to 40 m/s, for two liquid film thicknesses.

It was observed that both instabilities and disintegration of the liquid film are induced by the dynamic pressure and shear layer between the inner and outer air streams. The results support the "wavy bubble" mechanism of the liquid film disintegration for low inner air velocities. When the inner air velocity is low, the bubble at the atomiser's exit becomes unstable and bursts into poor quality atomisation. At higher air velocities the amplitudes of the liquid film instabilities sharply grow leading to pronounced shorter break-up lengths and, consequently, better atomisation. Aerodynamic forces have a major effect on fineness of atomisation. The aerodynamic interaction between the liquid film and the surrounding air increases the instability resulting in shorter break-up lengths and smaller droplets.

The findings of this work demonstrate that the ratio $(U_i/U_{\rm liq})^2$ is a key parameter in the atomisation process, and that the inner air velocity is the dominant characteristic, when compared with the influence of the outer air velocity. The deterioration of the liquid film close to the atomising edge of the nozzle is associated with a periodic process mainly dependent on the air velocity. Liquid flow rate, inner air velocity and initial liquid film thickness strongly affect the time and length scales of the break-up mechanism for reduced inner-air velocities ($U_i<40$ m/s).

The presence of the outer atomising air leads to a faster decrease of the break-up length, and this influence becomes stronger when swirl is imparted to the outer air, and for increasing swirl levels. For higher velocities of the inner air the break-up length shows smaller variations and the use of swirl in the outer air is seen to be highly effective in the obtention of a high quality atomisation.

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