Viscosity effects on the break-up of a liquid jet in a cross airflow

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This article presents an experimental study of the primary break-up of liquid jets in a cross airflow. This experiment was carried out in a specially designed facility. The measurement section was made of clear acrylic resin to allow optical access and visualization. The working liquid used in the present experiment was the aero-engine lubrication oil, which was injected perpendicularly into the airflow, via a nozzle from the top wall of the test-section. The effects of oil viscosity, and the jet and gas cross-flow velocities on the primary break-up mechanisms of the jet were studied. The main results showed that different break-up regimes were identified; column break-up and bag break-up separated by a transition zone. New correlation has been proposed for predicting the jet streamwise penetration before the break-up. This correlation was expressed in terms of the liquid/airflow momentum-flux ratio and Ohnesorge number.

1. Introduction

The interaction between a liquid jet and a cross flow is encountered in many engineering power systems. Typical examples include: (a) the injection of the lubricating oil, via a nozzle, into a rotating annular airflow in the cavity of aero-engine bearing chamber, and (b) the injection of liquid fuel into cross airflow in a combustion chamber. The complex mechanisms resulting form the interaction of a liquid jet with a cross gas-flow have been and are still the focus of many researchers internationally. In the following a brief literature review is reported to highlight recent published findings. Reference [2] studied experimentally the break-up processes of a liquid jet in a subsonic cross airflow. The authors of this reference tested different liquids, injector diameters and air cross-flow Mach numbers. They produced three expressions that combine the effects of liquid and gas Weber numbers to predict the effects on liquid jets column trajectories and jet transverse/penetration before breaking up. The transverse penetration distance of the jet before break-up normalized by the injector diameter was found to be proportional to the square root of liquid/airflow momentum-flux ratio, and the axial distance from the liquid injection point to the column fracture point was constant. In a subsequent publication, the same research group [3] investigated the spray structures of the atomization of liquid jets in a cross flow of air at subsonic Mach numbers where approaches to the distribution of the liquid fuel to desirable

locations were proposed. The authors of reference [4] studied the effects of the liquid injection angle on the break-up processes of water jets in subsonic cross-flows of air. Empirical correlations were proposed to predict the column trajectory, column fracture height and distance, and break-up regime parameters. The principal finding was that the jet penetration decreases with increasing the injection angle. Reference [5] investigated the disintegration of water jet in subsonic cross flow of air using water as the working liquid. This reference [5] showed that the break-up mechanisms that occur are mainly controlled by the gas Weber number. The shape of the jet depends most strongly on the momentum-flux ratio. Reference [5] described their break-up regimes as type I (when there is no effect of the cross flow of air on break-up), type II as arcade break-up, and type III as bag break-up. Recently, reference [6] extended the work of reference [5] to quantify the effect of those parameters, which have an influence on the properties of the primary break-up of liquid jets in cross-flows and the secondary break-up of drops. This reference [6] reported only the temporal properties of the primary break-up. New data has been also reported concerning the behaviour of the break-up of single drops under high-pressure conditions [7]. This would be equivalent to the second stage of jet break up. Reference [8] carried out an extensive study on the temporal properties of the secondary drop break-up at room temperature and atmospheric pressure, as well as at low range of liquid viscosities and non-turbulent jets conditions. All the above references have dealt with low-viscosity liquids, except for reference [6]. Though this reference (i.e, [6]) used high viscosity liquids; their analysis concerned only temporal properties of the primary break-up. A recent report [9] suggests that changes in the liquid viscosity could lead to drastic changes in the liquid break-up processes.
The aim of the present experiment was to extend the research work reported by the references mentioned in this introduction. The main focus of the present experiment was on the investigation of the role of the liquid viscosity on the primary break-up mechanism of a liquid jet interacting with a cross airflow. Various liquid temperatures (i.e., different oil viscosities) and jet and air velocities were explored.

2. Experimental Facility

Experiments were carried out using an open circuit wind tunnel shown schematically in Figure 1. This experimental apparatus along with the experimental conditions were well described elsewhere [10]. In this article only a brief description is reported. The wind tunnel consists of a centrifugal fan, a tunnel/duct comprising a test section, a jet nozzle and its assembly, an oil tank with four electrical heaters, and an oil-air separator. Different flow rates of air were produced by altering the rotational speed of the centrifugal fan up to a maximum speed of 2850 rpm. The test section has a cross section of 150 x 150 mm and a length of 325 mm. The maximum airflow velocity in the test section was approximately 22 m/s. The test section was made of clear acrylic resin to allow optical access for flow visualisation and imaging of the events. A set of electrical heaters was placed in the bottom of the tank to heat the oil to the desired temperature so that the oil viscosity could be altered to different values. The allowable maximum oil temperature was limited to a maximum temperature of around 60ºC because of the deterioration of the acrylic resin at high temperature. The liquid was injected via a nozzle that has a diameter of 1.0 mm. An oil storage tank, a pump, a filter, a valve, a thermocouple and a pressure transducer were used to control and measure the liquid flow before injection. The experimental conditions explored in the present investigation were summarized and reported in Table 1.
The airflow velocity profiles in the test section were obtained using a Pitot-static tube. Whereas the visualization and imaging of the jet break-up in the cross airflow were obtained

using a stroboscope to freeze the event and a standard video camera to capture and image the event.

Table 1: Experimental conditions*

u_{cf} (m/s)	v_j (m/s)	μ_L (Pa s)	ρ_L (kg/m^3)	ρ_{cf} (kg/m^3)	ρ_L/ρ_{cf}
6.2 – 18.4	0 – 5.8	0.019 – 0.058	944 - 981	1.2	808 - 826
q	We_j	Re_j	Oh_j	Re_{cf}	W_{cf}
15 -284	141 –1,119	36-292	0.11-0.333	69,423-206,549	1.6 –13.8

* u_{cf}: Cross airflow velocity; v_j: Jet velocity; μ_L: Liquid viscosity; ρ_L: Liquid density; ρ_{cf}: Airflow density; q: Jet/air flux ratio; We_j: Jet Weber number; Re_j: Jet Reynolds number; Oh_j: Ohnesorge number; Re_{cf}: Cross flow Reynolds number; W_{cf}: Cross flow Weber number.

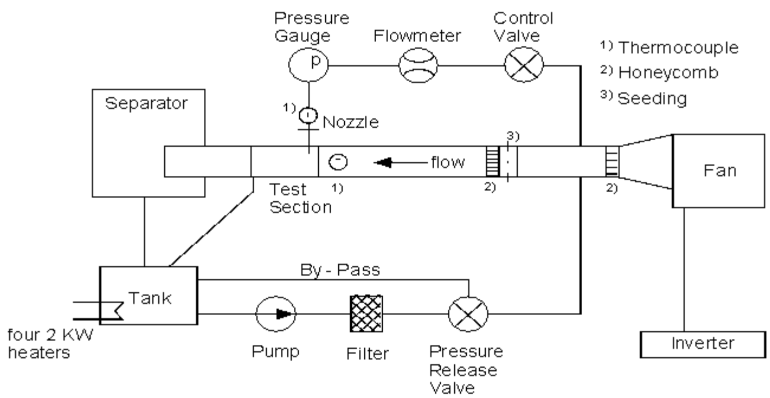

Fig. 1 Schematic diagram of the experimental set-up

3. Results and discussion

In this experimental investigation three parameters were varied independently: the oil viscosity, and the jet and air velocities. For each combination of conditions, approximately 25 images were processed and the resulting information averaged to extract information. This was necessary to ensure the repeatability and consistency of the acquired experimental data. The regimes of the primary jet break-up, the jet break-up locations and time to break-up of the liquid column have been all investigated. Some of these data were reported in [10].
Observations of the jet break-up showed that no break-up occurred when injection was into quiescent air, i.e., without cross airflow, even at very low jet velocities. This might be due to the small size of the test cross section, which is approximately 150 times the jet nozzle diameter. The oil jet was seen to hit the bottom surface of the test section before breaking up. Whereas, the presence of a significant cross-flow caused the oil jet to be bent and re-directed towards the direction of the airflow. Two types of jet break-up (termed type II and type III) have been identified for the present explored ranges of conditions. These two types are called column break-up and bag break-up as suggested by reference [5], respectively, and are separated by a transition regime. Two typical images of type II of the jet break-up are presented in Figures 2a and 2b, to show the column break-up. Increasing cross flow velocity yields similar break-up process of the jet as shown in Figure 2a; however, in this case the curvature of the jet column before break-up is increased and exhibits a form of break-up named “arcade-type” by reference [5], and shown in Figure 2b. Also typical images as examples of type III, i.e., bag break-up regime, are displayed in Figures 3a and 3b. Because of higher aerodynamic forces of the cross flow the thin layer bulges and forms bubble-like

bags on the lee side of the jet column. Further, the "explosion" of the bags results in small drops. The influence of the velocities of the jet and the cross airflow can be seen clearly in Figures 3a and 3b. Higher air velocities causes the jet to bend much earlier resulting in a lower transverse penetration of the oil jets. This effect is accelerated by the lower concurrent injection velocity of the oil into the cross airflow (see Figure 3b).

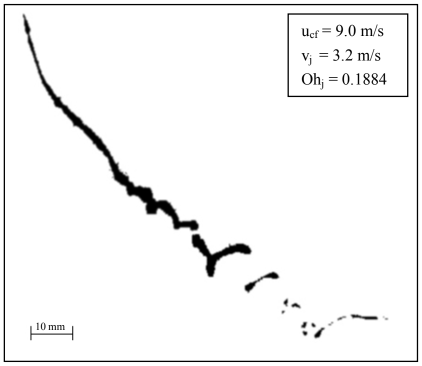

Fig. 2a: Column type-jet break-up

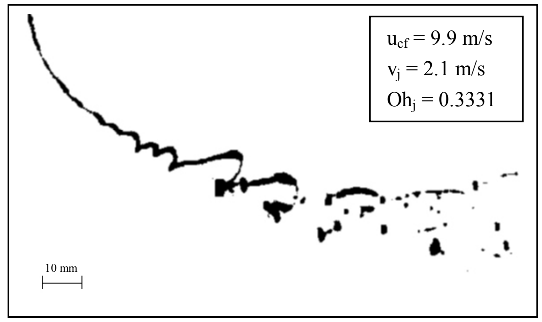

Fig. 2b: Column type-jet break-up

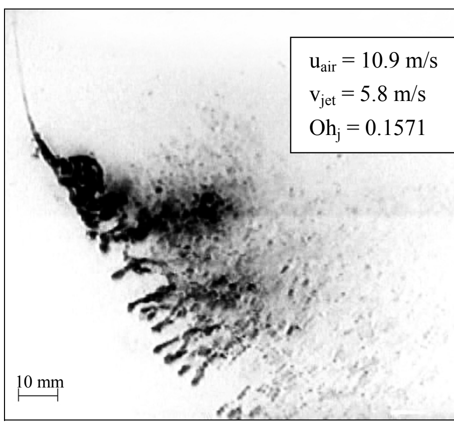

Fig. 3b: Bag type-jet break-up

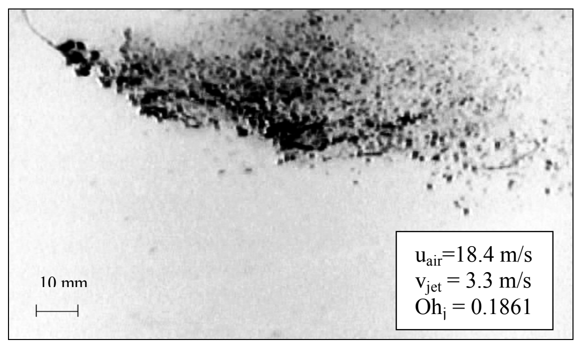

Fig. 3b: Bag type-jet break-up

To identify the different types of liquid break-up modes only one of the following parameters; air velocity, jet velocity and oil viscosity, was varied at the time. For each experiment, the parameter being varied was gradually increased from a minimum to a maximum value. These experiments showed that the passage from one break-up regime to another does not happen suddenly but that there is a transition region over which the regime of break-up is a hybrid between the two regimes bounding it. The role of the jet/air momentum-flux ratio, i.e., q, and the liquid jet Weber number, We_j, on the type of break-up can be seen in Figure 4. Weber numbers of the cross airflow, We_{cf}, and the liquid Weber number, We_j, have an influence on the cross sectional deformation and longitudinal instabilities of the jet, respectively. Liquid Weber number, We_j, is plotted, in figure 5, against the cross flow Weber number, We_{cf}. At higher liquid and cross flow Weber number, the bag break-up regime dominates, and vice versa; however, at lower liquid and air Weber numbers only the column break-up regime occurred. The classification displayed in Figure 5 agrees with the results obtained by [5,6], in which they described that the bag break-up mode may occur at higher, We_{cf}, and the column break-up at lower values of We_{cf}.

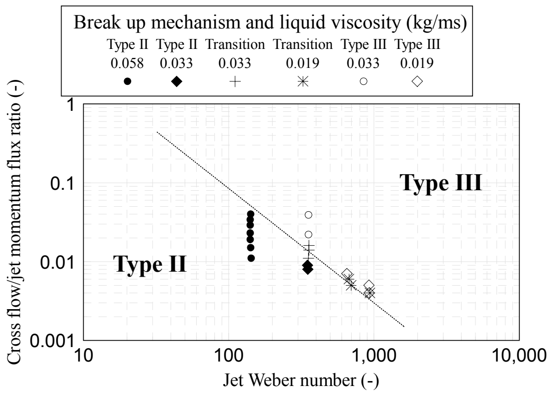

Fig. 4: Regimes map of break-up processes of an oil jet in a cross airflow

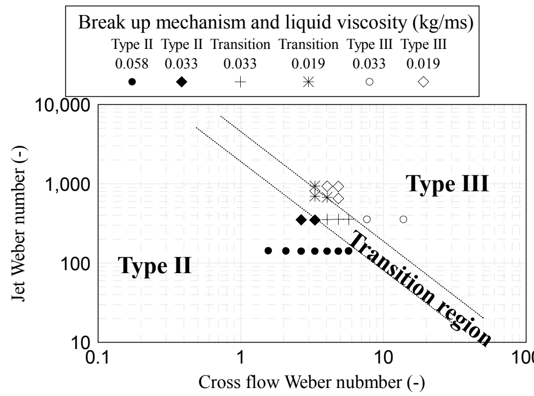

Fig. 5: Break-up regime dependence on We_j and We_{cf}

Figure 6 shows the evolution of the dimensionless streamwise (x-direction) penetration, i.e., x_b/d_N, of the jet as a function of the cross-airflow flux ratio for various liquid viscosities (i.e., Ohsenerge number). This figure shows that for any given liquid viscosity the normalized streamwise penetration decreases as the cross airflow velocity increases. However, for any given cross airflow velocity the streamwise penetration of the jet increases as the liquid viscosity increases.

An attempt was made to find an empirical correlation that can predict the streamwise penetration (x-direction) made dimensionless by the jet nozzle diameter, i.e., x_b/d_N, of the liquid jet before break-up as a function of all the involved parameters. The result was shown in Figure 7. This figure shows that at lower liquid viscosities up to approximately 0.029 Pa s, the normalized streamwise penetration of the jet tends to be almost constant and independent of the jet/cross-airflow momentum flux ratio, q. This result agrees well with the findings in references [2,6]. However, for liquid viscosities higher than 0.029 Pa s and up to 0.058 Pa s, this figure shows that the normalized streamwise penetration of the jet increases with increasing momentum flux ratio, q, and becomes also dependent on the liquid viscosity (accounted for here by using Ohnesorge number). This behaviour differs and disagrees with the findings of, for instance, references [2,6] where they found that the normalized streamwise penetration of the jet is constant and independent of q. As a result of the present experiment the following correlations were proposed:

$$\frac{x_B}{d_N} \approx 0.0037q + 14.10 \qquad \text{for } \mu_L < 0.029\ Pa\ s$$

and

$$\frac{x_B}{d_N} \approx 542.64 q^{0.87} Oh^5 \qquad \text{for } \mu_L > 0.047\ Pa\ s$$

However, due to the limited range of the explored conditions in this experiment, other experimental investigations may be required to confirm the trend of these new findings by exploring larger ranges of jet and airflow velocities.

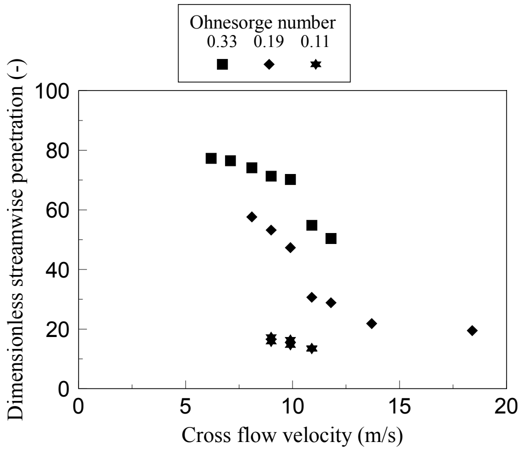

Fig. 6: Evolution of the normalized streamwise jet penetration as a function of the cross airflow velocity.

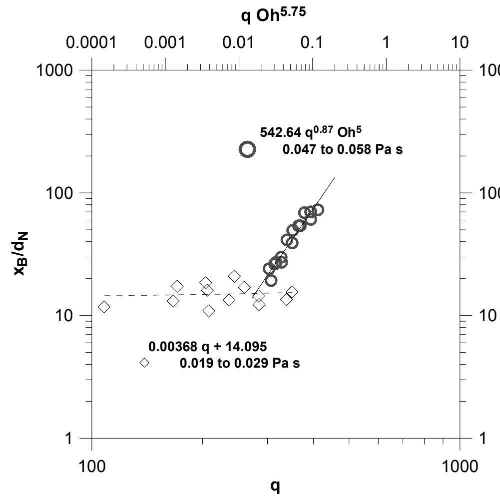

Fig. 7: Evolution of the normalized streamwise jet penetration versus the jet/cross airflow momentum flux ratio and Ohsenerge number.

4. Concluding Remarks

An experimental study of the primary break-up of a liquid jet in a cross airflow was reported. From this study the following remarks can be drawn: (*i*) The liquid viscosity seems to affect greatly the liquid jets break-up mechanisms; (*ii*) A new correlation to predict the jet streamwise penetration before break-up has been presented in this article; (*iii*) Due to the limited range of the experimental conditions explored in this investigation, additional experiments are underway to confirm the present findings under wider range of experimental conditions.

5. Acknowledgements

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