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BEHAVIOUR OF SMALL DIAMETER EVAPORATING JETS

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ABSTRACT

The behaviour of small diameter evaporating jets issued into a low pressure environment is experimentally studied. Charged Coupled Device (CCD) cameras connected to a computerised data logging system are employed for high speed imaging. Experiments at different jet velocity and environmental pressures have been performed with pure ether and ethanol and also the mixture of the two. Results indicated that there exists complex instability structures during the evaporation of the jet. Experimental evidence of these structures are presented here.

INTRODUCTION

There are many engineering and industrial applications in which the evaporation of liquid jets and droplets occurs. Relevant situations may be those of combustion, spray cooling, destruction of hazardous liquid wastes, vapour explosion and others. The "classical" disintegration of fine jets is usually associated with Rayleigh's varicose instability which dates back to 1897. This is primarily due to axisymmetric capillary disturbances which eventually grow with time and lead to pinching the jet into a regular row of droplets. The distance to this disintegration is proportional to the diameter of the jet, and increases monotonically with the jet velocity and the inverse square root of the surface tension. In this case, when the liquid jets are suddenly issued into a high temperature or low vapour pressure environment, the superheated interface between the liquid jet and the surrounding may become also unstable. This instability can greatly affect the hydrodynamic and thermal processes as well as the geometry of the jet.

In most practical situations, the jet may be a multi-component mixture of liquids with different degrees of volatility. As such a multi component droplet or jet moves through an evaporation chamber, the more volatile liquid vaporises earlier and its concentration near the surface is rapidly depleted. By diffusion dominant lateral mass transport in the liquid, the more volatile component may be trapped in the jet interior, and heated fast enough to reach limits of superheat. In such conditions homogeneous nucleation results, and a sudden jet rupture is to be expected.

The present study is concerned with an experimental investigation of evaporation from a small diameter jet of liquid being issued into a gaseous low pressure vacuum chamber. To this end, an experimental apparatus and novel measurement and visualisation equipment has been designed and built. In order to obtain a basic understanding of the evaporation process, experiments have been performed with single component liquids (ether and ethanol). Further, the experiments were extended to a mixture of the two liquids.

EXPERIMENTAL APPARATUS

The overall schematic of the experimental apparatus is shown in Figure 1. The rig consisted of a cylindrical steel plenum chamber of 700 mm in diameter and 1,000 mm high which was connected to a vacuum pump. The nozzle, from which the jet was issued vertically downwards was installed in a cubical enclosure (on top of the chamber) with plexiglas side windows. A servo-motor traversing mechanism was used to displace the nozzle in the vertical direction. The nozzle was fed via Teflon tubes from a pressurised liquid container equipped with a fine mesh filter. The nozzle consisted of several parts which were carefully machined from stainless steel and copper. It had interchangeable heads allowing production of jets with diameters in the range of 100 to 400 μm. The pressure inside the plenum chamber of the nozzle was modulated by a piezoceramic device. This also allowed generation of drops as well as a jet. A proper choice of the frequency allowed production of nearly mono-dispersed droplets oscillating in axially symmetrical modes. The details of the nozzle assembly and as well as droplet formation are given elsewhere (Hiller and Kowalewski, 1989 and Becker et al., 1991).

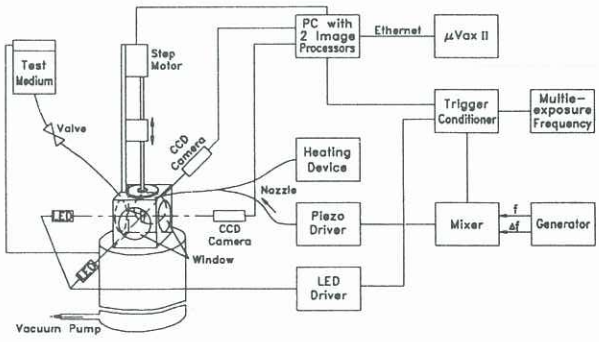


Fig. 1 – Schematic of the experimental apparatus

For the purpose of visualision, the jet was illuminated with two Light Emitting Diodes (LED), placed perpendicular to one another in the side walls of the cubical observation enclosure. The LEDs were powered by a specially designed pulse generator which triggered them as desired (Hiller et al., 1987). For recording the images of the illuminated jet, a novel high speed video imaging technique described by Hiller and Kowalewski (1989) was adopted. Two conventional

Charged Coupled Device (CCD) cameras (Sony XC77CE) were placed in two side walls of the cube each facing one of the LEDs. The cameras were connected to a personal computer equipped with two image processing cards. Specially developed software captured images, digitised, and then recorded them as binary files. The personal computer was connected to a micro-Vax computer which served as a mass storage of the files.

In some experiments in order to follow the fast developing transient effects on the surface of the jet, the special frame transfer feature of CCD cameras was used. Due to the movement of sensor charges during the transfer cycle, observed effectively as a movement of the sensor plane, short sequences of images can be registered (like in a classical streak camera). A commercially available CCD sensor (Thomson TH7863 CDT) was adopted to achieve very high-speed image recording. By modification of the frame-transfer drive-pulse sequence, two fields of the video frame are shifted continuously without interruption. The minimum time necessary to transport the whole image along the columns of the sensor matrix depends on the camera, which for the sensor used was 160 μs. This shifting period could be adjusted to a maximum of 20 ms. Due to the movement of sensor charges, observed effectively as a movement of the sensor plane, short sequences of spatially separated images can be registered. For a sequence of ten images a typical temporal resolution of 16 μs could be achieved.

For droplets, the imaging technique allows determination of the radius from the digitised images. The measured diameter variation (in time) is directly related to the droplet evaporation rate. Also from an analysis of the droplet oscillation frequency (Hiller & Kowalewski, 1989) it is possible to measure time dependent variation of the droplet surface tension. Once the variation of the surface tension with temperature is known, or has been measured by another method (e.g. static ring method), the technique can be used to indirectly determine the surface temperature of the evaporating droplet.

RESULTS

Experiments have been performed with pure ethanol or ether and also a mixture of the two. They were chosen because they are both single component and have quite different saturation pressures at normal ambient temperatures. The plenum chamber pressure was varied from 10 Pa to 100 kPa and the jet velocity was in the range 2 to 12 m/s. Prior to each experiment the filter in the liquid tank was replaced and then the tank was filled and sealed. For each experiment performed at the sub-atmospheric pressure, the plenum chamber was evacuated to the desired pressure. Some experiments were also performed at atmospheric pressure. This corresponded to two different regimes of evaporation. In the case of nearly atmospheric pressures, the evaporation process is relatively slow, mainly controlled by the rate of vapour diffusion from the surface. The presence of external gas may additionally affect evaporation rate due to a lateral gas flow close to the nozzle. The growth rate of instability waves may also be influenced by aerodynamic effects at the surface. In the case of evaporation in a low pressure environment, the rate of evaporation is only limited by the gas-kinematic conditions at the surface. The influence of external gas on the surface instabilities is not expected to be significant. However, in either case, initial evaporation rate near the outlet of the jet depends primarily on the surface heat flux. Sample results for each liquid and the mixture are presented separately.

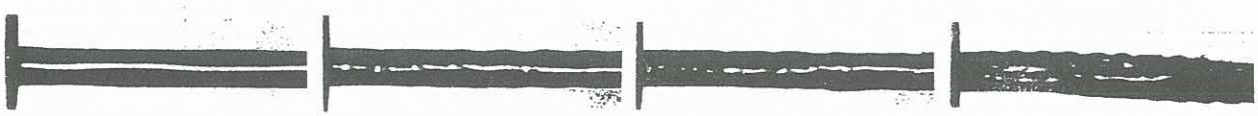
Ether

Fig. 2 shows 100 μm diameter jets of ether with different velocities issuing into the plenum chamber at a pressure of P_∞ = 100 kPa. The saturation pressure of the liquid was P_s = 58 kPa. It should be noted that the jets are always issued vertically downward, but the photographs are shown horizontally. The evaporation of ether at the pressure tested is mainly controlled by the diffusion of vapour into the surrounding neutral gas. At lower velocities the jet surface behaves like that of a non-evaporating jet, i.e. it is smooth and its break-up is well controlled by Rayleigh instability (Fig. 2). However, by a small increase of the jet velocity the surface becomes wavy and unstable. These characteristic surface waves start from the very beginning of the jet at higher velocities. The wavelength of this disturbance is approximately 1/4 of that typical of Rayleigh instability. The evident appearance of disturbances directly after the jet issues from the nozzle indicates that their growth rate is very high. This effect is somewhat less at lower jet velocities where fast ceasing of the initial disturbances with a recovery of the jet's stable shape can be observed. Figs. 3 and 4 show jets of diameters 200 and 400 μm respectively. A comparison of the jets with different diameters indicates that these surface instabilities mainly depend on the jet velocity. At least this is the case for the diameters tested, where instabilities appeared between 3.5 – 4 m/s.

The generation of strong surface disturbances for evaporating jets close to the nozzle can be expected, because at the starting point of the jet surface parameters (e.g. temperature and vapour mass flux) have their highest gradients. With an increase of the jet velocity, the evaporation rate becomes furthermore intensified by the lateral flow of unsaturated gas which is drawn into the regions close to the jet inlet. Far from the nozzle, the gas adjacent to the jet becomes rich in vapour and forms a coating around the jet which allows only a slow diffusion controlled evaporation. This reduction of the rate of evaporation may even lead to a dampening of the disturbances generated at the beginning of the jet, as a result of which smoothing of the jet surface far from the nozzle appears (see Fig. 2b). This can be easily detected from the shape of the bright streak seen at the jet axis. This streak appears due to the parallel light illumination of the transparent jet from behind. Any disturbance of the jet symmetry deforms this white streak (Figs. 2–4).

Ethanol

The experiments with ethanol were performed at a saturation pressure of 5.9 kPa with a low plenum chamber pressure of 0.1 to 5 kPa which allowed a variation in the rate of evaporation. Fig. 5 shows photographs of a 200 μm jet. A

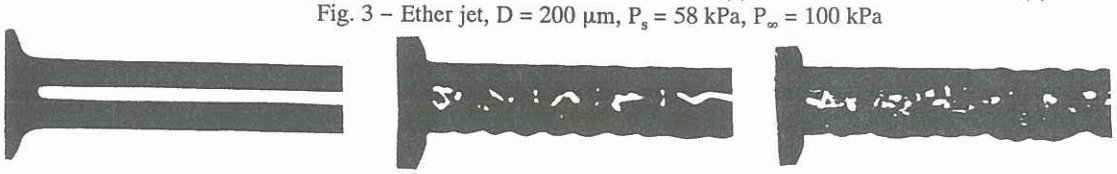


(a) 5 m/s (b) 5.6 (c) 7.5 (d) 10

Fig. 2 – Ether jet, D = 100 μm, P_s = 58 kPa, P_∞ = 100 kPa

(a) 3.3 m/s (b) 3.6 (c) 6 (d) 10

Fig. 3 – Ether jet, D = 200 μm, P_s = 58 kPa, P_∞ = 100 kPa



(a) 3 m/s (b) 5 (c) 7

Fig. 4 – Ether jet, D = 400 μm, P_s = 58 kPa, P_∞ = 100 kPa

(a) L/D = 60 (b) L/D = 0 (c) L/D = 0

Fig. 5 – Ethanol jet, D = 200 μm, V = 12 m/s, P_∞ = 5 kPa, P_s = 5.9 kPa

bending of the jet some 60 diameters downstream of the nozzle outlet is evident (Fig. 5a). This was also observed in some other experiments and generally it was found to be a stable shape. Far from the nozzle, the jet suddenly changed its direction and preserved its bent shape over a relatively long period of time (5 – 50 seconds). Similar behaviour in hot water evaporating jets have been observed by Charwart and Russali (1981). This phenomenon may be explained as a consequence of the combined effects of unsymmetrical evaporation and lateral fluid circulation in the bent cylinder. Once the jet bends, this lateral circulation intensifies heat transfer on one side of the cylinder, preserving the asymmetry in evaporation rate. Photographs 5b and 5c show that the evaporating surface of the jet right at the outlet of the nozzle is unstable as can be seen from the breaking up of the white streak. In fact, photograph 5c shows that the instability has grown just a few diameters downstream of the nozzle outlet.

If the liquid overheat is high enough, any adequately strong initial instability of the jet surface would be immediately amplified resulting in a drastic change in the shape and character of the jet. This can be clearly seen in Fig. 6. These instabilities which have a wide range of wavelengths are characterised with very short growth rates in the range of milliseconds. Therefore, if the jet surface becomes unstable, then well developed instabilities can be already seen at the beginning of the jet, close to the nozzle. Beside surface instabilities, another destabilising process at these low pressure environments, due to the heterogenous nucleation was observed. Small nucleation sites inside the jet can grow to form large bubbles leading to the jet breakup. An example of this can be seen in Fig. 7 where the jet at the exit of the nozzle (2 diameters downstream) has a cylindrical shape, however, at 120 diameters downstream, bubbles which have broken the jet up can be seen. It should be noted that at the conditions tested, the growth rate of such bubbles fairly slow (of the order of 1 m/s) and this process was only occasionally observed at large distances from the nozzle.

In some experiments, the jet was observed to disintegrate very close to the nozzle. As a result of this disintegration, a structure with a "spike" was formed (see Fig. 8 for time sequenced photographs) which appeared to maintain its shape over a period of a few minutes. It appears that, close to the nozzle, part of the layer of highly viscous overcooled liquid peels off from the jet surface and is kept in such a spike shape by the vapour pressure which is produced by the exposed hotter liquid surface beneath this layer. The experiments indicated that in general, even at very low external pressures (i.e. 100 Pa) it is often the case that the ethanol jet preserves its stable cylindrical shape. This is due to the fact that at low liquid temperatures, independent of the liquid superheat (given by the pressure ratio), the amount of internal energy is insufficient to completely evaporate the jet and evaporation is mainly limited to the surface of the jet. As a result of this, the overall geometry of the jet is preserved which is different to the behaviour of hot liquid jets (Chaves et al. 1988). Their observations indicated a strong disruption of the surface of hot superheated jets emerging into the atmosphere, when the internal energy of the liquid was high (which is specially the case for retrograde liquids).

At high evaporation rates but low initial temperatures fast cooling of the jet surface results in the creation of a cold "coating" layer of highly viscous liquid. This may explain the existence of long stable jets at environmental pressures well below the vapour pressure of the liquid. Such jets behave similarly to non–evaporating jets, and their stability can be investigated using external excitation with the help of the piezoceramic transducer. At very low pressures the high evaporation rate leads to the growth of instabilities, nucleation of bubbles and generation of the irregular surface structures. The jet surface is unstable although at the beginning it may preserve its cylindrical form. Once a small rupture in the jet surface appears, this leads to the complete disintegration of the jet's cylindrical shape.

The development of these evaporation induced instabilities is accompanied with a rapid change of temperature and mass flux at the interface. After an injection of superheated liquid into an environment of low partial pressure, its sensible heat momentarily causes flashing evaporation of the liquid surface.

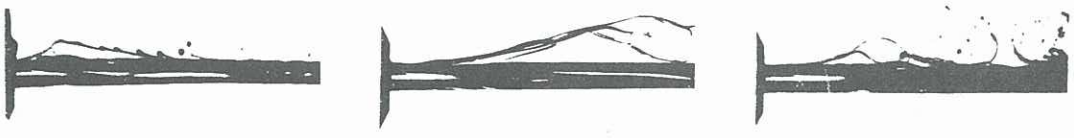
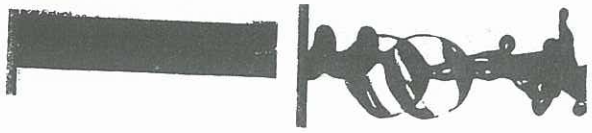
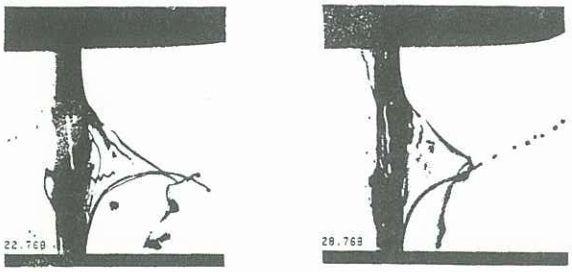


Fig. 6 – Ethanol jet, D = 200 μm, V = 12 m/s, P_∞ = 100 Pa, P_s = 5.9 kPa



(a) L/D = 2 (b) L/D = 120

Fig. 7 – Ethanol jet, D = 200 μm, V = 12 m/s, P_∞ = 5 kPa, P_s = 5.9 kPa



(a) t = 0 sec. (b) t = 24 sec.

Fig. 8 – Ethanol jet, D = 200 μm

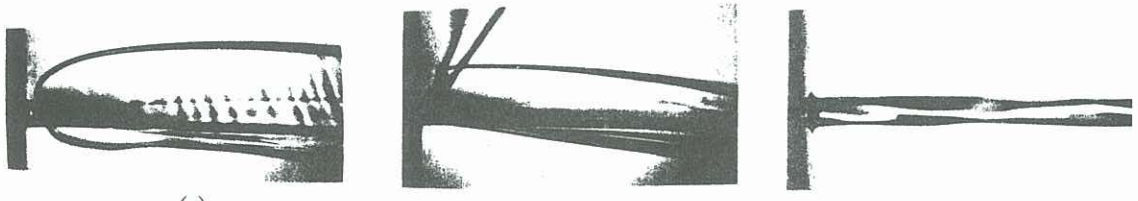
As a result, the surface temperature of the jet or droplet decreases rapidly and further evaporation is essentially controlled by an internal heat transfer mechanism. During this transient time, the temperature distribution in the liquid is highly non-uniform and its surface becomes dynamically very unstable.

The presence of small initial disturbances at the surface immediately leads to a non-uniform evaporation rate and surface tension. These in turn, lead to the observed surface turbidity, development of craters and shrinks at the jet and droplet surface and possible deflection of the jet direction.

Ether and Ethanol Mixture

Some experiments were performed with a mixture of ether and ethanol. The mixture was prepared by mixing equal volumes of pure ether and ethanol. Sample results for a jet of 100 μm diameter being issued into the plenum chamber at 100 Pa are presented. It was observed that the jet at the point of leaving the nozzle either became immediately unstable and formed a large complex film-like structure (Fig. 9a and b) or conformed to its stable cylindrical shape (Fig. 9c). Waviness of the film and cylinder can be observed which is due to some initial disturbances. This instability is believed to be due to the fact that right at the inlet of the jet, the more volatile liquid (i.e. ether) evaporates rapidly on the jet surface creating a cold slow-evaporating coating of ethanol.

In situations where the cylindrical shape of the jet was preserved, the formation of ethanol coating on the surface of the jet trapped some ether in the core of the jet. Further downstream, this trapped ether reached its nucleation point which lead to an explosive type of rupture of the jet and its disintegration into a conical film of liquid. This can be clearly seen in Fig. 10 which shows the jet some 100 diameters downstream of the nozzle.



(a) (b) (c)

Fig. 9 – Ether/ethanol mixture, D = 100 μm, P_∞ = 100 Pa

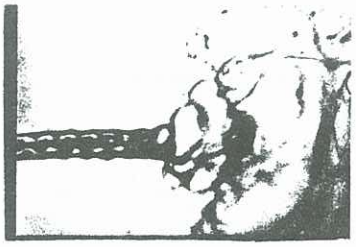


Fig. 10 – Ether/Ethanol mixture, D = 100 μm, P_∞ = 100 Pa, L/D = 100

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