Int. J. Multiphase Flow Vol. 16, No. 6, pp. 951–957, 1990
Printed in Great Britain.

0301-9322/90 $3.00 + 0.00

STRUCTURE OF THIN LIQUID FILMS IN GAS–LIQUID HORIZONTAL FLOW

G. F. HEWITT,[1,2] S. JAYANTI[2] and C. B. HOPE[1]

[1]Thermal Hydraulics Division, Harwell Laboratory, Didcot, Oxon. OX11 0RA, England

[2]Department of Chemical Engineering and Chemical Technology, Imperial College of Science and Technology, London SW7 2BY, England

(*Received* 6 *November* 1989; *in revised form* 1 *April* 1990)

Abstract—The structure of the liquid film in horizontal annular flow is studied visually using the refractive index matching technique. The liquid film is found to contain significant amount of air bubbles, which are continuously entrained, broken up and released by the rolling motion within the film. A new conceptual picture of the gas–liquid interface is presented.

Key Words: horizontal annular flow, thin films, bubble entrainment, wave structure, interfacial friction

INTRODUCTION

Horizontal annular two-phase flow occurs in a wide variety of industrial processes. The pressure drop and heat and mass transfer rates associated with this flow depend significantly on what happens at the gas–liquid interface. This paper reports on some novel flow visualization experiments conducted to study the film structure in horizontal annular flow.

EXPERIMENTAL DETAILS

The flow visualization experiments were conducted in a typical low pressure air–water test facility. The novel feature of our rig is the use of the refractive index matching technique for visualizing thin liquid films: two-phase flow occurs in a horizontal tube made of fluorinated ethylene propylene (FEP) which has a refractive index of 1.34 compared to that of 1.33 for water. Thus, if the tube is surrounded by a rectangular compartment filled with water as shown in figure 1, there will be little distortion of the light passing through the water/tube wall/water medium, which has virtually the same refractive index. This makes it possible to visualize thin *water* films in tubes of circular cross-section. The FEP material, however, has the disadvantage of being difficult to machine. Therefore the entire test section was made of a 8.5 m long piece of tubing. The inside diameter of the tube was 32 mm. Care was taken to keep the tube horizontal. Further details of the FEP material can be found in a forthcoming Ph.D. thesis by one of the authors (C.B.H.).

Two techniques were used for flow visualization: high-speed photography and photochromic dye tracing, though the latter was only partially successful. A visualization section was located at a distance of 7.5 m from the two-phase mixing section; this consisted of a water jacket of square section which surrounded the tube. Fused silica was used as the material for the water jacket because it transmits almost 100% of light from the UV through the vis to the IR region. High-speed video films with filming rates up to 6000 frames/s were taken from one or two directions, as shown in figure 1. Diffuse light from a 250 W bulb was used as the illumination source. Camera A was placed very close to the visualization section to get a high magnification factor. Still photographs were also taken to obtain the instantaneous structure of the liquid film. In this case, a high-intensity flash lasting only 2 μs was used as the light source. The objective of the photochromic dye tracing technique was to determine the velocity profiles in the liquid film. Here, a line trace was formed in the liquid phase by activating a water soluble dye (triarylmethane) which had been added to the circulating water. The activation was provided by a pulsed UV laser (wavelength 308 nm) which caused the dyestuff to change to magenta (reddish purple) along the path length. The subsequent convection/dispersion of the trace by the flow was recorded using high-speed photography. Further details of the technique are given by Fogwell & Hope (1987).

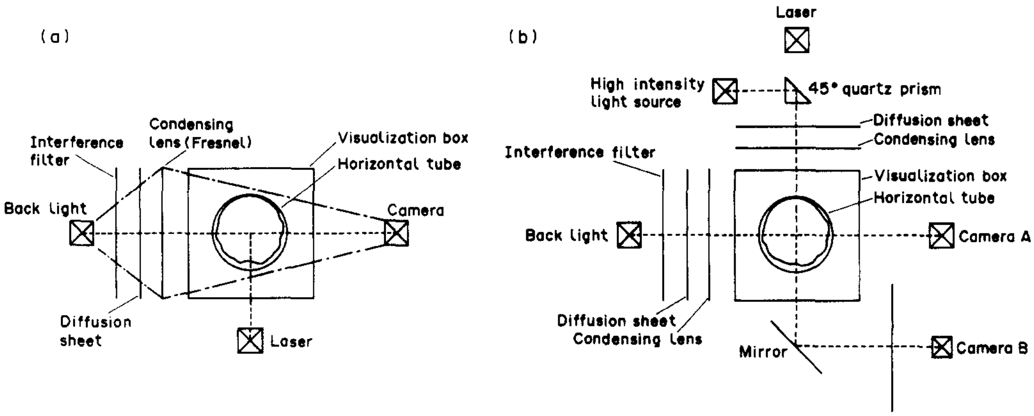

Figure 1. Schematic diagrams of the optical system: (a) single camera arrangement; and (b) dual camera arrangement.

RESULTS AND DISCUSSION

The range of air and water flow rates investigated is given in table 1. Though the range is small, it is believed that it was sufficient to bring out the essential features of the structure of thin films in horizontal annular flow.

A typical instantaneous structure of the liquid film at the bottom of the tube is shown in figures 2(a,b). The most striking feature of the film is the presence of a large number of air bubbles. Note that the film thickness is of the order of 4–5 mm in figure 2(a), whereas it is < 1 mm in figure 2(b). It can be seen that bubbles of all sizes—from a fraction of a mm to a few mm—are present, and that they extend right up to the wall. The larger bubbles are somewhat distorted by the shear in the liquid, although the smaller ones are nearly spherical and are convected with the flow.

The source of these bubbles is entrainment during the churning/rolling process that goes on continuously in the liquid film. This can be seen in the series of video frames shown in figure 3. These were taken by camera A (see figure 1); the time elapsed between successive frames is 1/6000 s. An air bubble is created [figure 3(a)] when a small wave rolls over itself, and is then carried forward by the flow. The video films also show two related features: the break-up of a larger bubble into smaller ones, and the release of a bubble [see the cluster of bubbles in figure 3(b)]. Thus, bubbles are continuously created, broken up and released within the film.

Such extensive bubble entrainment has not been observed in the high-speed ciné films of vertical annular flow. This is perhaps due to the action of gravity. In vertical upward flow, the gravity force and the shear force act axially; this helps in the entrainment of liquid into the gas core. In horizontal flow, the gravity force acts in a direction perpendicular to that of the shear force, and tends to make the wave roll forwards before its amplitude becomes sufficiently high for the wave crest to be sheared off. This would imply that the net rate of entrainment in horizontal annular flow would be less than in a corresponding vertical flow. This is consistent with the results of Dallman *et al.* (1984). It is not clear if the process of bubble release contributes significantly to the net entrainment of liquid droplets. The release of large air bubbles does lead to entrainment of large chunks of liquid

Table 1. Experimental conditions

Tube material	Fluorinated ethylene propylene
Inside diameter	0.032 m
Developing length	7 m
Refractive index	1.34
Test section pressure	1.05–1.35 bar abs.
Temperature	20°C
Air flow rate	0.016–0.047 kg/s
Superficial velocity	17–44 m/s
Water flow rate	0.075–0.180 kg/s
Superficial velocity	0.09–0.22 m/s

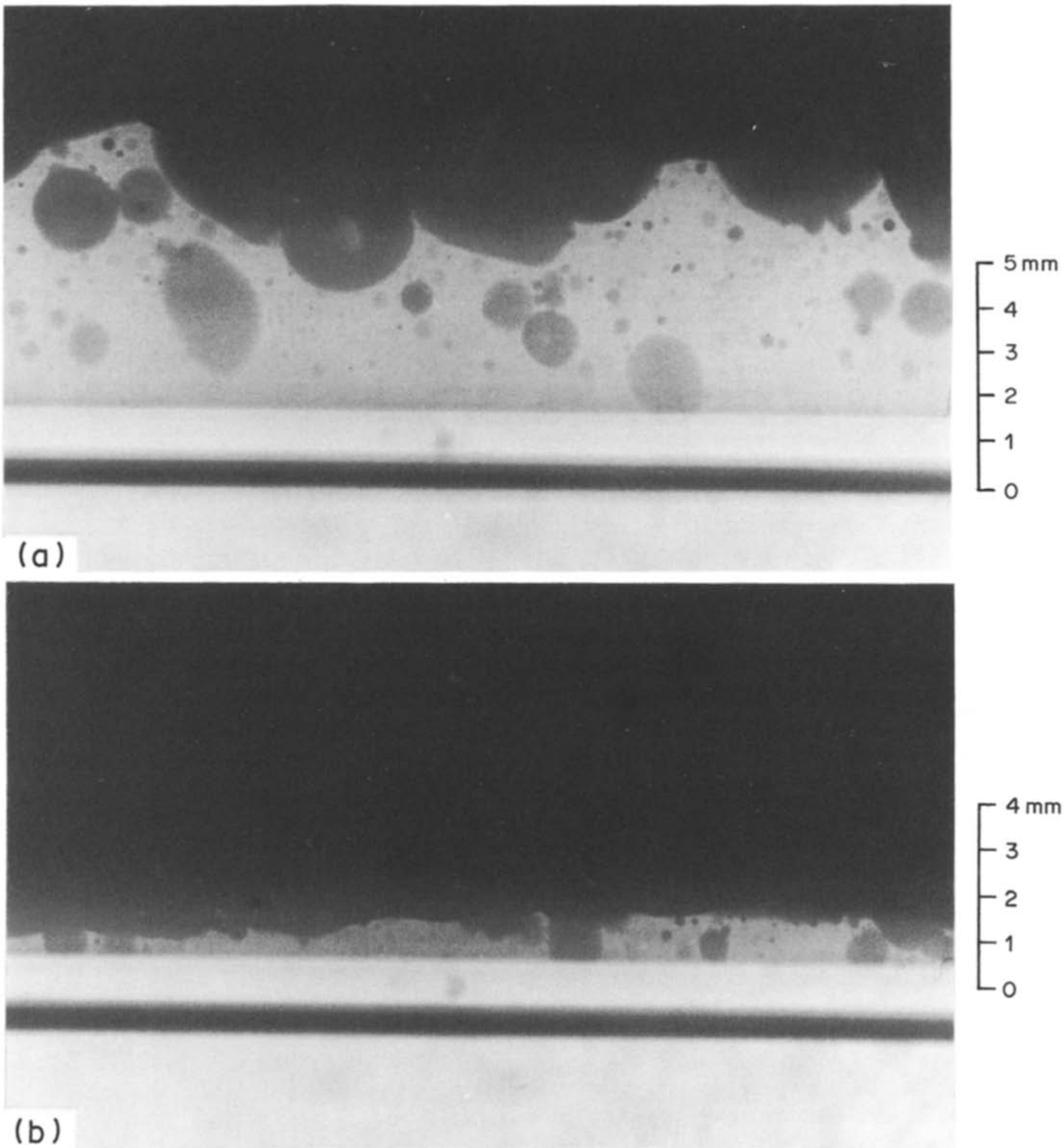

Figure 2. Instantaneous structure of the liquid film at the bottom part of the tube: (a) air flow rate = 0.026 kg/s and water flow rate = 0.100 kg/s; and (b) air flow rate = 0.041 kg/s and water flow rate = 0.100 kg/s.

(figure 4); however, they tend to redeposit very quickly. It is difficult to observe in our video films if part of this chunk is entrained in the form of droplets by the gas phase. If this were the case, one could expect wall heat flux to contribute more significantly to entrainment of liquid in horizontal annular flow.

The video films also show some interesting features of wave structure. Conventional wisdom has it that the gas–liquid interface is covered by small ripples and fairly regular disturbance waves with a relatively large wavelength/amplitude ratio. It is generally assumed that it is the latter that contribute significantly to interfacial friction (Lillehelt & Hanratty 1961; Jameson 1971). The present study shows (see, for example, figure 4) that within these disturbance waves there are many smaller roll waves with a wavelength/amplitude ratio of the order of unity. Between two successive disturbance waves, the film is relatively smooth, although small air bubbles can be found in these thin films. Thus, the traditional view of the liquid film in annular flow [figure 5(a)] is not quite correct; a more realistic model would be as shown in figure 5(b): patches of rough and smooth surfaces, the former characterized by three-dimensional "roughness elements" of the order of the local film thickness. From the point of view of deriving interfacial friction factor correlations, a

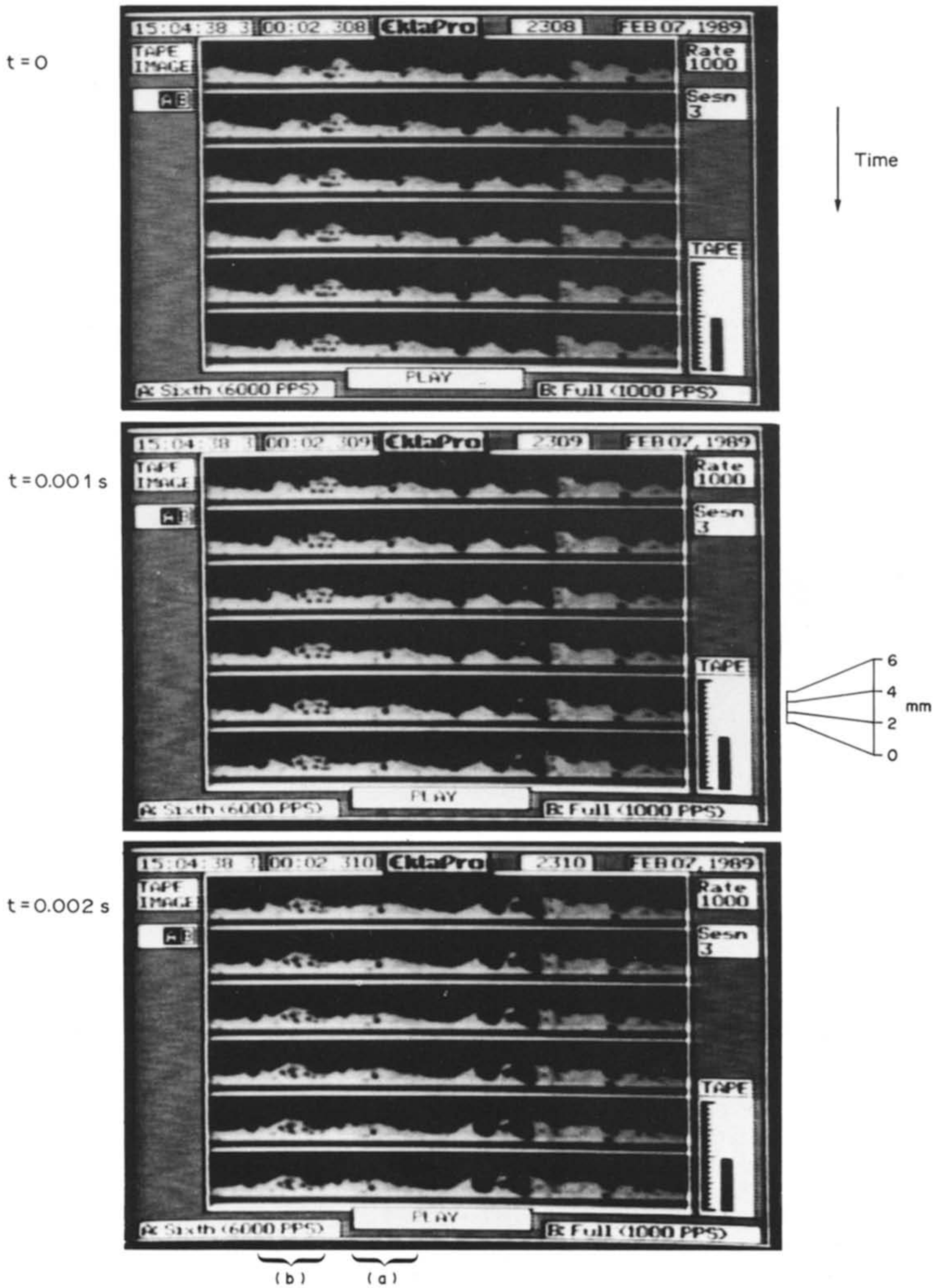

Figure 3. Illustration of the processes of (a) bubble entrainment and (b) bubble break-up and release in horizontal annular flow; air flow rate = 0.016 kg/s and water flow rate = 0.115 kg/s.

factor of intermittency can perhaps be used to account for the presence of rough/smooth patches on an otherwise smooth/rough surface.

This structure of the liquid film has not been observed in many of the previous studies of annular flow. The reason perhaps is that they used either axial viewing techniques (where the localized

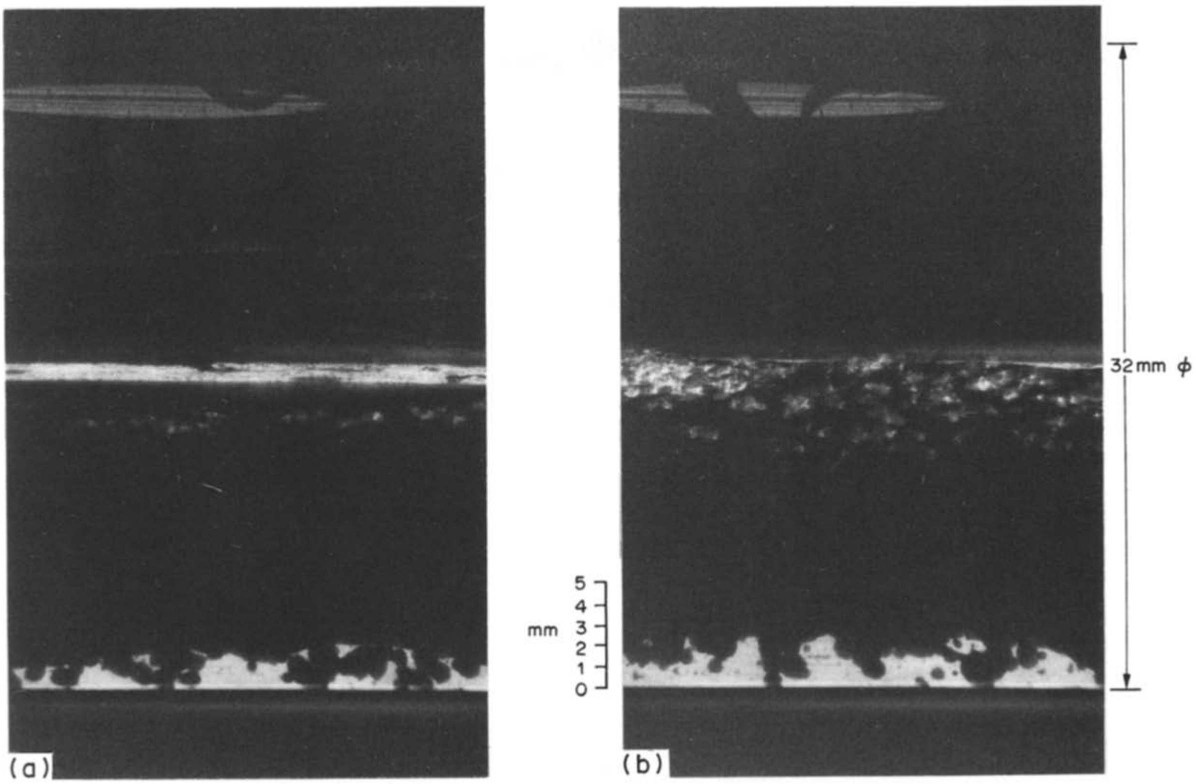

Figure 4. Entrainment of large chunks of liquid within the disturbance wave; air flow rate = 0.029 kg/s and water flow rate = 0.178 kg/s.

effects of bubble entrainment etc. would not be easily noticeable) or conductance probes (which do not give a localized film thickness measurement, and which do not indicate the presence of an air bubble). It is the use of the refractive index matching technique in our experiment that permitted visualization of very thin films. This technique has been used previously by Jacowitz & Brodkey (1964) to study the gas–liquid interface in horizontal annular flow near the entrance region of a pipe. They used turpentine to match the refractive index of their glass tube of 9.5 mm i.d. They also report the presence of air bubbles in the liquid film. However, the filming rate in their experiments was only 1000 frames/s, and consequently, the interface appeared blurred. The video films shown in this paper were taken at a rate of 6000 frames/s, and the still photographs at an exposure time of 2 μs (i.e. an effective filming rate of 500,000 frames/s). This improved the clarity of the photographs.

One of the objectives of the photochromic dye tracing experiments was to establish the presence, if any, of circumferential flow in the liquid film. This is of interest in determining the mechanisms contributing to the distribution of the liquid film in horizontal annular flow (Jayanti *et al.* 1989). The experiments were only partially successful, in that the rapid turbulent diffusion of the dye trace made it impossible to detect any circumferential flow. (This does not imply that there is no circumferential flow, but only that the technique cannot be used to detect it, if there was any.) However, the experiments yielded the axial velocity profiles in the liquid film. Two types of velocity profiles were observed, as shown in figures 6(a–d): the distorted S-shaped profile expected in thin film flow subjected to interfacial shear [figures 6(a,b)]; and a distorted parabolic profile [figures 6(c,d)] which occurred within a wave, and which reflected the rolling motion of the wave crest. This would belie the assumption that the wave crest moves faster than the main body of the wave. Our

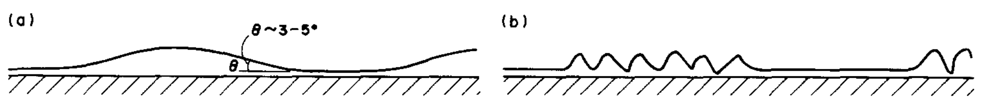

Figure 5. Conceptual picture of the gas–liquid interface: (a) traditional view; and (b) proposed view.

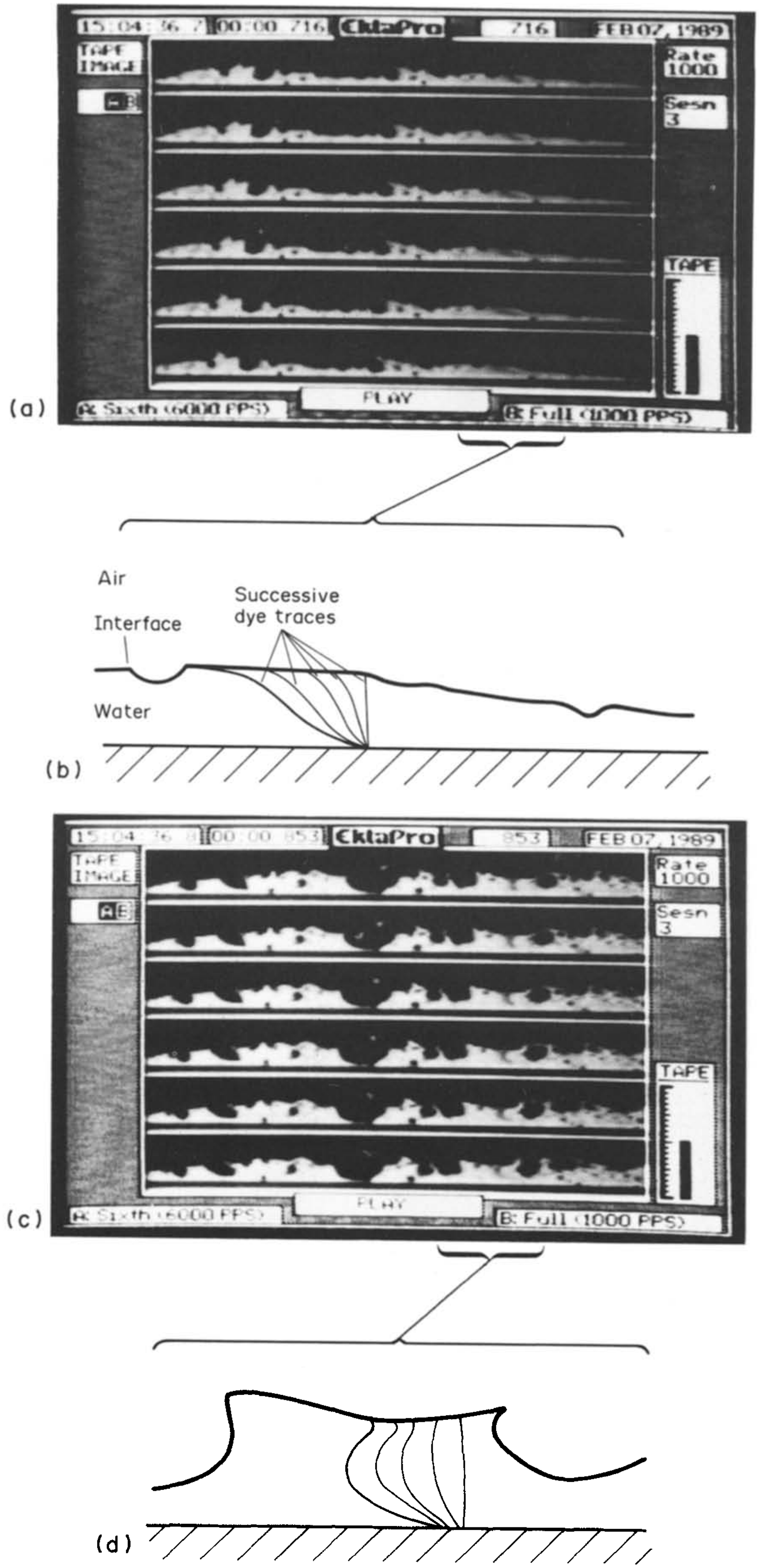

Figure 6. Evolution of the dye trace indicating (a,b) a distorted S-shaped axial velocity profile and (c,d) a parabolic profile.

observations show that the wave crest is deformed continuously by the gas shear and that it exchanges mass and momentum not only with the gas phase but also with the bulk of the wave.

To summarize, the liquid film in horizontal annular flow is found to contain a significant amount of air in the form of bubbles. These air bubbles are continuously entrained, broken up and released by the rolling motion within the liquid film. This should considerably augment both heat and mass transfer between the phases. The structure of disturbance waves is very complex; within the large wavelength disturbance waves, many roll waves can be found, the wavelength of which is of the order of the wave height. A new conceptual picture of the gas–liquid interface is presented; this would imply that the pressure drop attributed to disturbance waves hitherto is significantly under-estimated.

Acknowledgement—The authors wish to thank the Photographic Group at Harwell for some painstaking work. The work described in this report was undertaken as part of the Underlying Research Programme of the UKAEA.

REFERENCES

DALLMAN, J. C., LAURINAT, J. E. & HANRATTY, T. J. 1984 Entrainment for horizontal annular gas–liquid flow. *Int. J. Multiphase Flow* **10,** 677–689.

FOGWELL, T. W. & HOPE, C. B. 1987 Water soluble photochromic dyes for flow visualisation. *Expl Heat Transfer* **1,** 141–154.

JACOWITZ, L. A. & BRODKEY, R. S. 1964 An analysis of geometry and pressure drop for the horizontal annular two-phase flow of water and air in the entrance region of a pipe. *Chem. Engng Sci.* **19,** 261–274.

JAMESSON, G. J. 1971 The contribution of disturbance waves to the overall pressure drop in annular two-phase flow. *Trans. Instn chem. Engrs* **49,** 42–48.

JAYANTI, S., HEWITT, G. F. & WHITE, S. P. 1989 Time-dependent behaviour of liquid film in horizontal annular flow. UKAEA Report No. AERE-R13487.

LILLEHELT, L. U. & HANRATTY, T. J. 1961 Relation of interfacial shear stress to the wave height for concurrent air–water flow. *AIChE Jl* **7,** 548–550.