It is always helpful to add a schematic
of the experimental setup when possible.

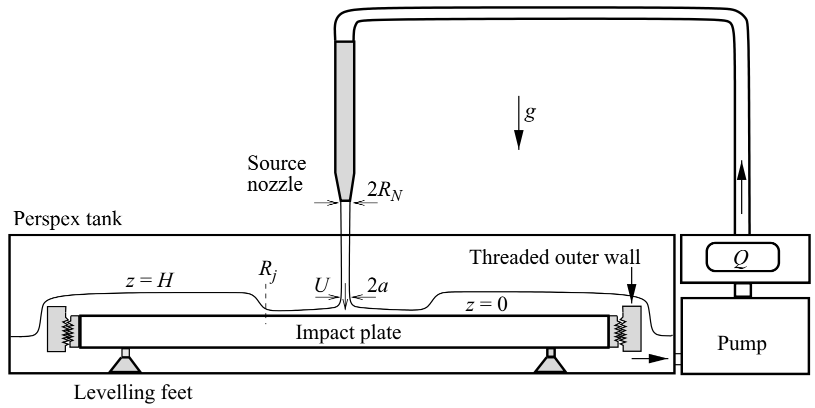

FIGURE 1. A schematic illustration of the experimental apparatus. Fluids were pumped through the source nozzle with a prescribed flux Q. The outer depth H was controlled by an outer wall whose height was adjustable.

unsteady. Liu & Lienhard (1993) characterized the dependence of the resulting unsteady jump forms on the governing dimensionless groups. The observed dependence on the jump Weber number clearly indicated the significance of surface tension on the jump stability.

Ellegaard *et al.* (1998) identified that a striking instability may transform the circular hydraulic jump into steady regular polygons. Experiments were conducted with ethylene glycol and a source nozzle of radius 0.5 cm at elevations of 1–5 cm above the lower boundary ejecting fluxes between 30 and 50 ml s^{-1}. The dependence of the jump planform on the nozzle height and flux rate was reported by Ellegaard *et al.* (1999); however, the dependence of the flow structure on the governing parameters was not fully elucidated. While a suggestion was made that the jump forms could be understood if an effective line tension was ascribed to the jump, no clear mechanistic explanation of the instability was given. We here extend the experimental study of these authors in order to gain further insight into the problem.

In § 2, we describe the experimental technique employed in our study, and in § 3 describe the variety of jump shapes observed in our exploration of parameter space. In § 4, we identify the dimensionless groups that govern the system, and detail the dependence of the jump form on these parameters. The dependence of the mean jump radius of the asymmetric forms is investigated in § 5. A scaling argument for the dependence of the wavelength of instability of the steady asymmetric jumps on the governing parameters is proposed in § 6.

2. Experimental technique

Figure 1 is a schematic illustration of our experimental apparatus. Fluids were pumped through the flowmeter and source nozzle, resulting in a falling jet that impacted the centre of a circular glass target plate of diameter 36 cm. The nozzle height was varied between 1 and 5 cm above the target plate. Beyond the hydraulic jump, the fluid ultimately spilled over the edges of the reservoir, and was recycled through the pump. The reservoir depth H was controlled by an adjustable outer wall and measured with a micrometer point gauge 3 cm from the outer edge of the reservoir. The asymmetric jump structures were extremely sensitive to any variations from horizontal; consequently, great care was taken in levelling the system in order to ensure that the reservoir spilled uniformly over the bounding outer wall. The system was levelled to 1 part in 24 000 by adjusting its three support legs, and measuring the deflection from horizontal of the impact plate and reservoir rim with a Sterret level. The position of the jump was measured from radial gradations on the target plate surface.

The variable flow pump (Cole Parmer, Model 75225-00) was capable of fluxes in the range of 0–100 $\mathrm{ml\,s^{-1}}$ for the fluids examined in our study. The flow rate was measured with an AW Company Model JFC-01 digital flowmeter accurate to 0.1 % over the range considered. Viscosity measurements accurate to 0.14 % were made with Cannon-Fenske Routine tube viscometers. Fluid density was measured with an Anton-Parr 35N densitometer, accurate to 0.01 %. Surface tension measurements accurate to 0.1 $\mathrm{dyn\,cm^{-1}}$ were made with a Kruss K10 surface tensiometer. The bulk of the experiments were conducted with glycerol–water solutions with viscosities in the range 1–35 cS, densities 1.0–1.2 $\mathrm{g\,cm^{-3}}$ and surface tensions between 60 and 70 $\mathrm{dyn\,cm^{-1}}$. We also used a pure mineral oil (Crystal Plus 70FG Oil, STE Oil Company Inc.), for which $\rho = 0.83\,\mathrm{g\,cm^{-3}}$, $\nu = 11\,\mathrm{cm^2\,s^{-1}}$ and $\sigma = 29.7$ dyn. Finally, we incorporate the data of Ellegaard *et al.* (1999), who used ethylene glycol for which $\rho = 1.1\,\mathrm{g\,cm^{-3}}$, $\nu = 11\,\mathrm{cm^2\,s^{-1}}$ and $\sigma = 47.7\,\mathrm{dyn\,cm^{-1}}$. Outer layer depths were varied from 0.2 to 1.5 cm.

Four nozzles were used, of radii 0.2, 0.38, 0.45 and 0.5 cm. The inner nozzle surfaces were smoothed and tapered near their exits in order to suppress turbulence and encourage laminar outflow in the parameter regime considered. While the details of the cross-sectional flow profiles were not measured, the nozzles were designed according to the specifications of McCarthy & Malloy (1974) with a narrow taper in order to flatten the profiles. Their suggestion is that the jet profiles will be relatively flat provided the taper angle lies between 45° and 70°. A recent study by Bergthorsson *et al.* (2005) demonstrates that the jet profiles will in general depend on the nozzle length, taper, and the jet Reynolds number and that, in certain ideal situations, the three may be varied in order to ensure a flat jet profile. While tuning these control parameters in order to ensure that the jet profiles are perfectly flat was not practical for our study, we worked from the assumption that the jet profiles are flat to leading order. A series of experiments was performed to test the sensitivity of the jump structure to the nozzle design. Turbulence generated in the nozzle by the addition of an obstacle was evident in the irregular, perturbed surface of the jet and that of the resulting jump. Two nozzles with identical outlet radii (0.32 cm) but different tapers (45° and 70°) were examined, and found to produce indistinguishable jump forms. Intervening taper angles were examined through addition of mylar sheets inside the nozzle with the sharper taper; over the range of Reynolds numbers and tapers considered, no qualitative changes in jump form were observed.

Flow speeds could be measured by tracking microbubbles introduced in the source fluid using a Redlake Motionscope Model PCI 8000S high-speed video camera. Adequate resolution of the bubbles typically required that we record at 500 frames per second with 0.001 s exposure times. The video footage was analysed using Midas Version 2.08 particle tracking software.

3. Observations

The variety of strictly circular jumps that may arise has been documented by Craik *et al.* (1981) and Liu & Lienhard (1993). Owing to its relevance to the jump stability, we recall here the transitions of the circular jump that arise as the outer depth is increased, from Type I to IIa and IIb jumps (see figure 2). We follow Ellegaard *et al.*

Justification of the chosen method/experimental setup

Specific details necessary for replication of the experiment.

Standard method cited