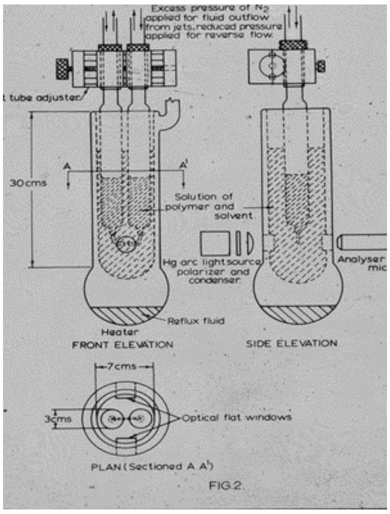
# Bristol Extensional flow Apparatus

## Extensional Flow; Opposed Jets

The first apparatus I designed and had built was not invented by me. It was the inspiration of the late Sir Charles Frank with input from the late Andrew Keller. Both were total scientists of the highest calibre and I happened to be the fortunate PhD student at Bristol University Physics Department in 1970 tasked with the job of turning their ideas into experimental reality. Sir Charles had been reading papers by Pennings et al (1970) and  Peterlin (1966) on the polymer chain stretching power of extensional flows and Sir Charles proposed an untried geometry of firing polymer solution into the faces of each other using two opposed jets. High strain rates were required and the whole thing needed to be at elevated temperature with optical windows if flow induced fibrous crystallisation of polyethylene was going to be observed. Andrew Keller suggested using a glass reflux bath arrangement and with the combined skills of a superb glassblower in Physics, Mr Colin Burrows and Andrew Keller’s talented but feisty technician Terry Owen, an apparatus was constructed that could blow and suck fluid into opposed jets. I discovered the sucking flow was far more stable than blowing and the apparatus is shown in figure 1 with the resulting observed localised flow birefringence, Frank et al (1971), Mackley et al (1975). Chain extension and fibrous crystallisation was achieved, but at the time of writing up my PhD an explanation as to why the extension was localised on the exit symmetry axis of the geometry was not clear.

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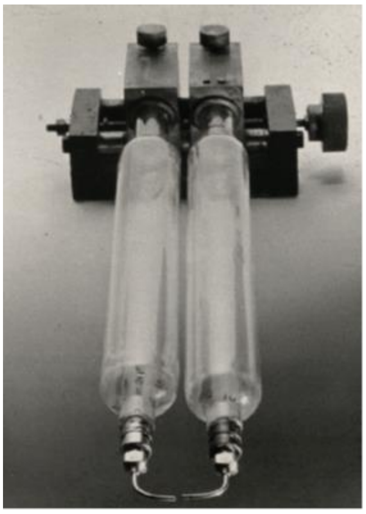

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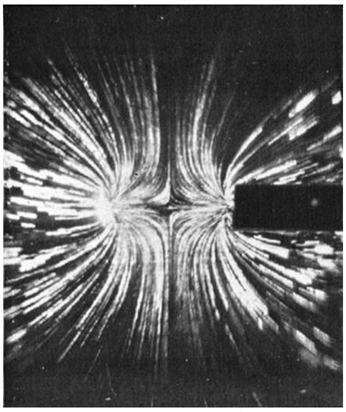

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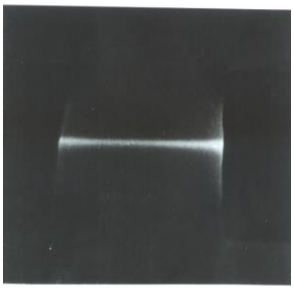

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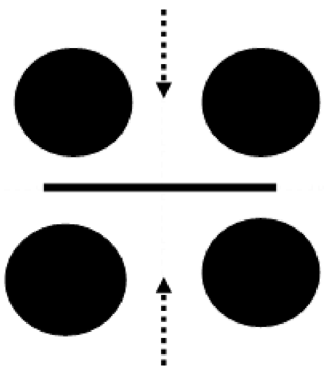
a) Schematic of Opposed Jet apparatus. b) Photograph of Opposed jets.

c) Streamline photograph of uniaxial extension flow. d) Photograph of localised centre line birefringence for PE/Xylene solution. (Mackley et al 1975).

## Extensional flows. Two, Four and Six Roll Mills.

The reason for the observed localised birefringence only became "obvious" after a series of further experiments were carried out using other centro symmetric flow geometries, namely the Two and Four Roll Mill. The Four Roll Mill was the invention of G.I Taylor (1934) where he had used the apparatus to follow the stretching of drops in pure extensional flows. My observations using the Four Roll Mill were carried out as a combined student final year research project at Bristol using polyethylene oxide/water solutions, which were very much more benign than elevated temperature polyethylene/xylene solutions, (Crowley et al 1976). Localised birefringence was again observed in the Four Roll Mill as shown in Figure2. On seeing the results, Charles Frank immediately realised that in order to stretch chains in solution, not only was a high strain rate required, but also a high strain too and in the opposed jet and mill geometries this was only achieved very close to the exit symmetry axis or plane of the flow. The conclusion, once appreciated was obvious and goes a long way to explaining why there were so many reports of different extensional rheometers apparently giving different extensional viscosities, see for example James et al (1994), Petrie (2006). Very few extensional rheometers reach any where near high enough strain levels to obtain full chain extension and or a steady state. Most extensional rheometers measure some form of transient extensional viscosity.

The Two Roll Mill, (Frank et al 1976) which was one of my own inventions for flow birefringence experiments, is shown below and added a touch of rotation to the flow. The Six Roll Mill,(Berry et al 1977) was the inspiration of Sir Michael Berry and is also shown below. The Six Roll mill literally took the multi mill story to catastrophically high levels!



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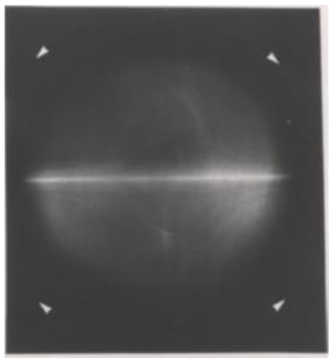

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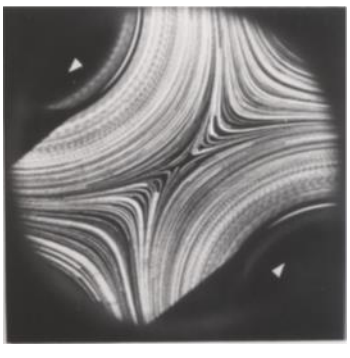

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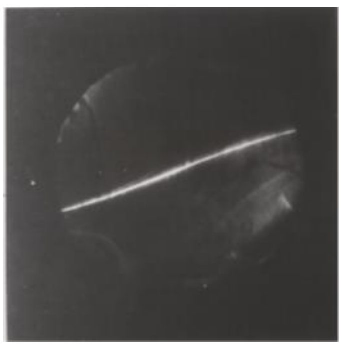

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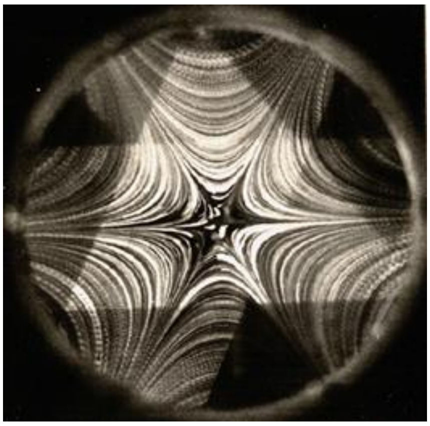

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a) Schematic of Four Roll mill. b) Localised birefringence for PEO/water solution in Four roll mill. c) Photograph of streamline flow for Two Roll mill. d) Photograph of localised flow birefringence for PEO/water solution. e) Photograph of Six Roll Mill.  f) Photograph of streamlines for six Roll Mill.

(Crowley et al 1976, Frank et al 1976, Berry et al (1976))

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