

Streaming Birefringence - A Step Forward

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Abstract. An investigation into three dimensional fluid flow has been conducted which combines the use of Computational Fluid Dynamics (CFD) simulations with the experimental phenomenon of Streaming Birefringence. A versatile flow channel was designed and built for use in conjunction with a circular polariscope. The experimental liquid used was an aqueous solution of a dye, commercially known as Milling Yellow NGS with the addition of Sodium Chloride. To extract the flow fields, six image phase stepping photoelasticity was used over backward and forward steps, and flows around a cylinder, and full-field fringe data were obtained. This method needs laminar flow regimes and the Reynolds number of the flow was around 10. To allow direct comparisons of the CFD solutions with the optical results, a macro (UDF) was written to interpret the flow field results from a (FLUENT6) CFD simulation. This integrated the shear stresses across the flow field and banded the results into fringes. A good correlation between the simulated fringes and the shear-strain rate was obtained from these observations.

Introduction

Photoelasticity is based on the phenomenon that certain materials, when loaded, exhibit temporal double refraction, or birefringence, when viewed in polarised light. In particular, the extent of this double refraction is found to be proportional to the amount of shearing force in the material [1] and as a result, the concentrations of shear stress are represented as visual contours or 'fringes'. This present study is concerned with an analogous phenomenon in the experimental study of fluid dynamics known as streaming birefringence, streaming double refraction or flow double refraction [2].

In photoelasticity and the study of loaded solids, obtaining practical photoelastic materials which are cheap and transparent, whilst remaining optically sensitive and physically useable is paramount. For streaming birefringence a similar specification is required. However, fluids differ from solids, principally due to their inability to sustain a shear stress when a force is applied [3] and thus continually deform as long as the shearing force remains. By definition, streaming birefringence therefore requires the use of a liquid or gaseous medium to represent the resulting shear stresses produced from relative motion only characterised in a *moving* fluid. Historically, certain pure liquids or liquid solutions have been found to exhibit adequate levels of birefringence and have been successfully combined with photoelastic theory during the late 1950's, for analysing shear stresses in two-dimensional laminar flows [3]. In addition, the phenomenon has also been employed as a flow visualization technique in qualitative studies to observe regions of separation, reattachment and transition [4], which are clearly distinguishable using this technique.

Streaming birefringence offers unique advantages over existing experimental techniques in fluid dynamics as it visually shows a real-time change in shear stress across the full flow field and, provided the flow remains laminar and approximately two-dimensional, can be used to quantitatively determine velocity profiles across the flow domain. In addition, the technique is unobtrusive and can therefore be useful in small experimental channels in which pitot-tubes or hot wire anemometers could otherwise introduce large errors. These advantages, combined with its

ability to clearly define flow phenomenon, also make it useful as a means of experimentally validating two and three-dimensional laminar simulation results. The rapid development and now widespread use of Computational Fluid Dynamics (CFD) within engineering emphasizes the importance of such validation.

The disadvantage of the technique, however, is that the fringes produced represent an integral of the shear stress along the light path, and if the shear stress changes along this path, then the interpretation of the fields can be problematic. Considerable advances have been made in integrated photoelasticity in recent years with the development of automated systems [5, 6, 7, 8, 9], but the obvious potential of birefringent fluids has not been exploited. This research explores the use of automated phase stepping photoelasticity and Computational Fluid Dynamics (CFD) simulations to study three dimensional fluid flow.

Birefringent Flow Theory

There have been several theories to explain the phenomena of flow birefringence which include that of Rosenberg [10] who suggested that the effect was due to deformation of molecules. This implies that the interference fringes are related to the maximum shear stress in the fluid, τ_{\max} , and not the streamlines as previously assumed. Therefore the effect is governed by the stress optic law [1]:

$$2\tau_{\max} = \frac{N\lambda}{cd} \quad (1)$$

where N is the order of the fringe observed, c is the stress optic coefficient, d is the length of the light path in the fluid and λ is the wavelength of the light.

Shear stresses in a substance arise due to the strain of its adjacent layers relative to one another; and the cohesive forces acting in-between, which attempt to restore equilibrium. In a moving fluid, when neighbouring particles in the flow begin to move relative to one another as a result of a difference in their relative velocities, shear stresses are created such that they resist this relative motion and consequently deform the fluid's original shape (Figure 1). It follows from this analogy, that there can be no shear stress in a fluid which is at rest or at constant velocity at every point, since the fluid particles are at rest relative to each other [3].

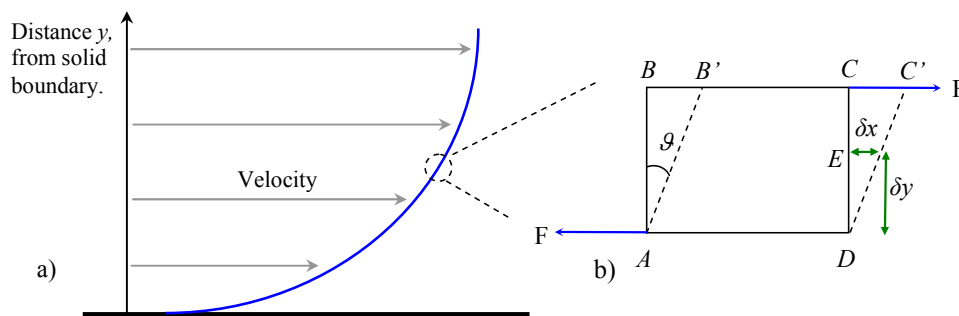


Figure 1 a) Variation of velocity with distance from a solid, stationary boundary in laminar flow, b) deformation of a fluid element caused by shearing forces.

From experiment, it has been found that shear stress is proportional to the shear-strain rate [3] and is known as Newton's law of viscosity:

$$\tau = \mu \frac{\partial u}{\partial y} \quad (2)$$

where μ is the viscosity and du/dy is the change in velocity, perpendicular to the velocity direction.

Streaming birefringence therefore only occurs in birefringent fluids which are subject to shear stresses. From the theory of photoelasticity, as the polarised light wave enters the birefringent medium, it will split into two orthogonal waves travelling at speeds proportional to the principal stresses and the vibrations of these waves will be parallel to the principal stress directions. Hence on exiting the medium the waves will have an optical phase difference directly related to the difference in the principal stresses which is directly proportional to the maximum shear stress. This means that as the stress varies within the fluid, the optical phase difference also changes. So the total birefringent effect along the light path is clearly the integral of the magnitude and direction of the shear stresses of the fluid, τ ,

$$\tau_{total} = \int \mu \left(\frac{du}{dy} \right) dy \quad (3)$$

This fact is particularly important for real, three dimensional flow, because a shear occurs at the walls giving additional fringes due to the integrating effect. It was postulated that if a calibrated map of the integrated shear stress can be found across the flow domain using the principles of photoelasticity, then it could be used in qualitative and quantitative comparisons with data from CFD analyses. Hence the method of phase stepping [11] was used to obtain a full field map of the isochromatic fringe order of the of the fluid flow for three different flow cases which were also modelled using CFD. It is believed that automated photoelasticity has never been used previously for streaming birefringence.

Experimental study

The experimental liquid used was an aqueous solution of a dye, commercially known as Milling Yellow NGS¹ and was prepared using a 0.55% concentration (by weight), with the addition of 0.289 % concentration (by weight) of Sodium Chloride. This fluid had been used with great success in the 1950's by Peebles et al [12] and details of experiments on concentration may be found in the work by Swanson [13]. The fluid was unavailable for about two decades from the 1980's due to health and safety concerns which appear to have been overcome recently.

A versatile flow channel of a modular design was designed so that various obstructions and steps could be installed easily in it. This channel is shown in Figure 2. It had an expansion section to allow the flow boundaries to be well controlled and stress-free glass sides to ensure no additional fringes were introduced due to the channel material. This method needs laminar flow regimes and the Reynolds number of the flow was around 10.

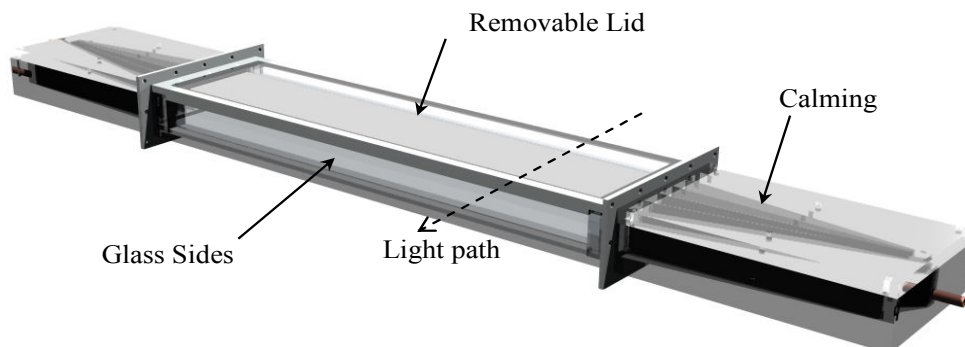


Figure 2 Flow channel design (internal dimensions flow section: 30.5mm x 104mm x 500mm)

This flow channel was positioned so that it could be viewed through a circular polariscope. This and the experimental equipment needed to control the flows is shown in Figure 3.

¹ supplied by City Chemical LLC, 139 Allings Crossing Road, West Haven, CT 06516, USA

Three obstructions were inserted into the flow channel: a backward step; a forward step; and a cylindrical obstruction. A range of flow velocities were investigated and the temperature of the fluid was monitored in order to maintain a uniform viscosity. For each obstruction an image of the dark field isochromatic fringe orders was recorded and these are shown in Figure 4. To obtain full-field, quantitative fringe data, six image phase stepping photoelasticity [11, 14] was used. and the fringe maps are shown in Figure 5. The six intensity images were recorded sequentially before being processed using freely available software² developed at The University of Sheffield, therefore it was essential that the flow was steady state and laminar. It would be possible to record unsteady flow using an instrument with real time phase step capture capability (e.g. a poleidoscope [15]).

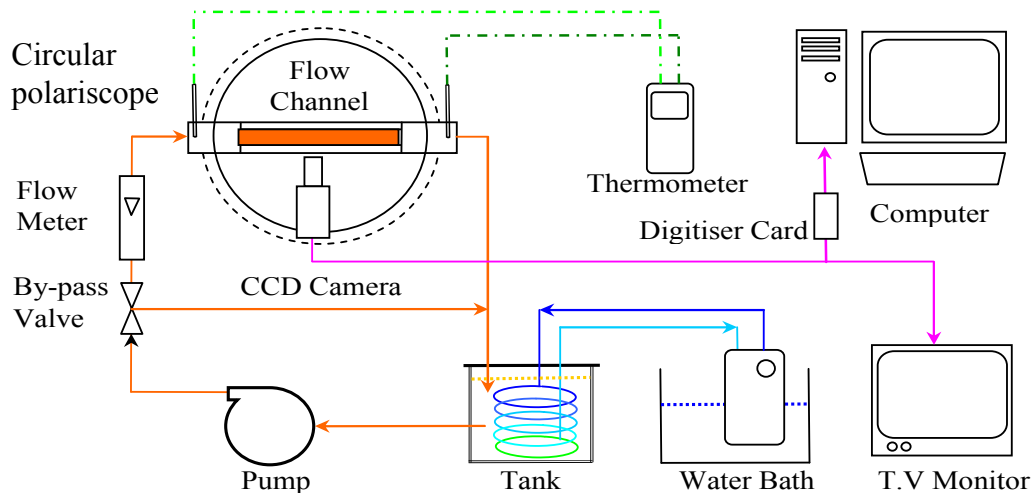
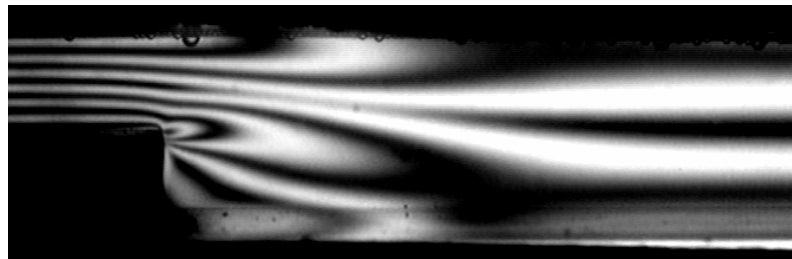
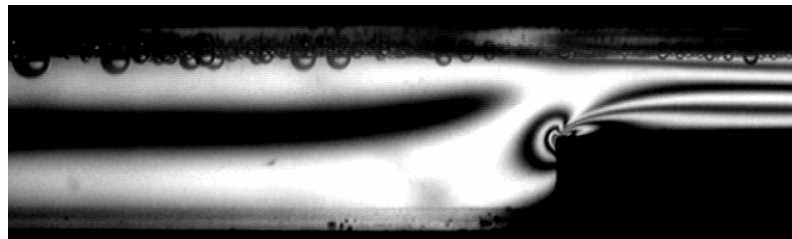


Figure 3 Schematic of the apparatus

a) Backward Step
0.05 m/s inlet velocity.
20.6°C.



b) Forward Step
0.028 m/s inlet velocity.
21.1°C.



c) Cylinder Obstruction
0.025 m/s inlet velocity.
20.4°C.

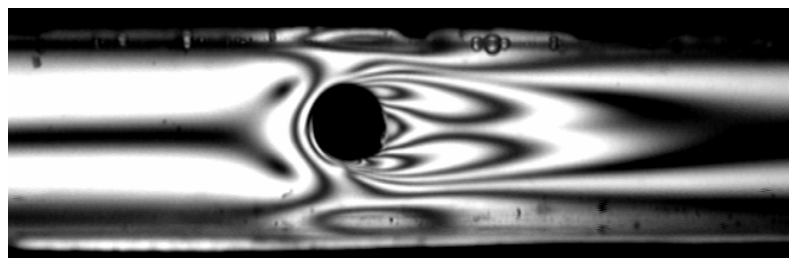


Figure 4 Showing the isochromatic fringes in a dark field circular polariscope for the fluid flow over a) a backward step, b) a forward step and c) a cylindrical obstruction.

² www.experimentalstress.com

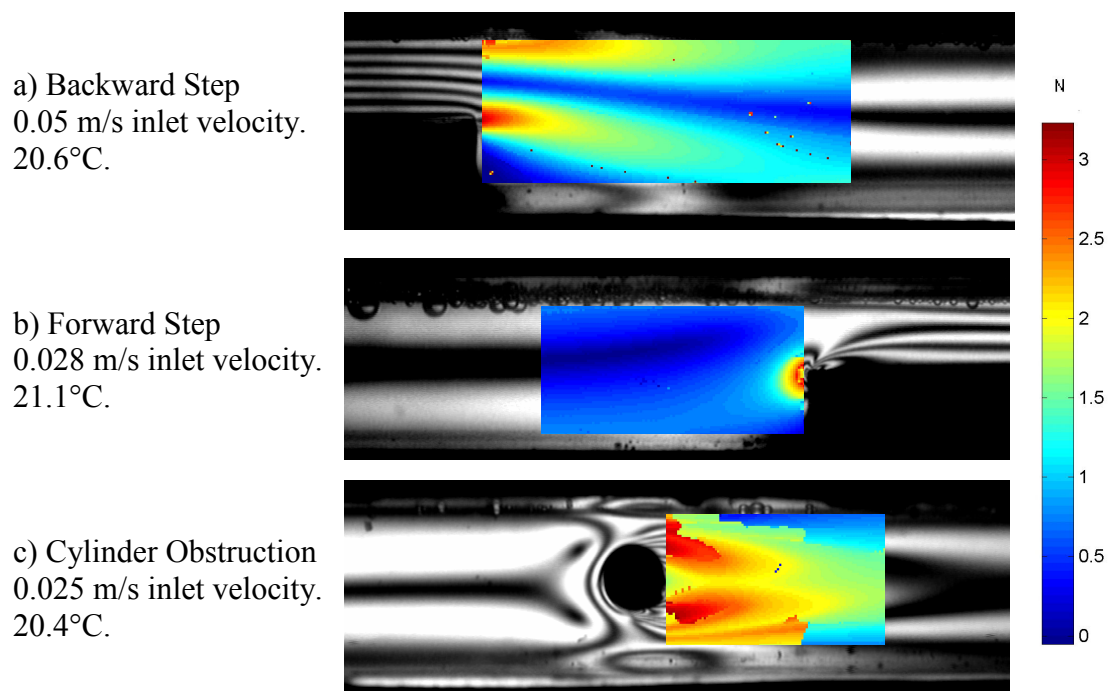


Figure 5 Full-field maps of isochromatic fringe order obtained from six image phase stepping, superimposed over the photographs from Figure 4.

CFD study

To allow direct comparisons of the CFD solutions with the optical results, a macro (UDF) was written to interpret the flow field results from a (Fluent 6) CFD simulation. The macro integrated the shear stresses across the flow field and banded the results into fringes. Typical results from this process are shown in Figure 6 along with the associated isochromatic fringes.

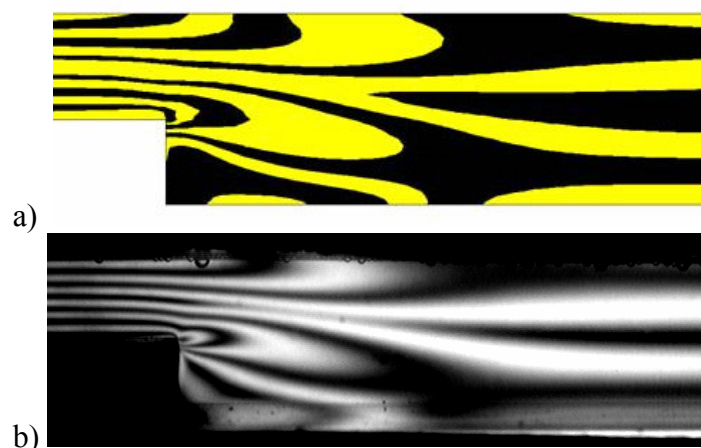


Figure 6 a) Arbitrary colour map applied to shear-strain rate CFD data from the forward step at 0.05 m/s compared with b) the isochromatic fringes

Discussion and Conclusions

The clarity of the fringes shown in Figure 4 confirms that the Milling Yellow NGS works well as a birefringent fluid with sufficient optical sensitivity for automated analysis which is clearly shown in Figure 5. The phase stepping method allowed full-field quantitative fringe analysis from the

birefringent flow; it is believed that this is the first time that such an automated photoelastic method has been applied to fluid flow as no other groups appear to have the expertise in both automated photoelasticity and fluid flow. The main limitation which was observed in these data is that the unwrapping algorithm [14] still fails at a high fringe concentration, as seen in Figure 5(c). This problem can be overcome with a higher optical magnification.

Qualitatively, a good correlation was obtained between the simulated fringes from the CFD models and the experimental photoelastic fringes, which is shown in Figure 6. However for quantitative analysis a calibration method still needs to be developed in order to obtain a relationship between the fringe order and the shear stress. This could be obtained from analysing the fully developed flow in the entry section which is well understood, or with the use of a calibration cell with a known shear rate and fringe order [2]. This methodology is currently being explored.

If it were possible to predict accurately the fringes from a suitable numerical model, then that model could be validated against the full field experimental fringes. This would lead to a far greater understanding of the flow

This technique is currently limited to laminar flow, but it could still see use in the analysis of boundary layers within turbulent fields. This work has also shown that the non-Newtonian properties of the fluid are no restriction to being able to model the flow fields.

In conclusion, the method of using phase stepping streaming birefringence can show the magnitude of the shear stress and thus of the flow. This technique is beginning to show great promise and further flow geometries and calibration methods are currently under investigation.

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