

# Flow Visualization in Turbulent Large-Scale Structure and Flow Control Research

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## Abstract

It is now generally accepted that most turbulent shear flows have a characteristic large-scale structure (LSS). The resulting task is to determine what the LSS is for any particular flow that one is interested in modelling or controlling. If it is not a well studied flow where the LSS is already known, then the wisest course of action is to learn what the LSS is using the most efficient techniques at your disposal. Careful use of experimental flow visualization is one of the quickest, cheapest, and surest ways to discover the qualitative nature of the flow LSS. Although significant progress has been made in using evolutionary algorithms to find optimum control techniques, in actual application one must have an idea what levers are at one's disposal before one can devise practical control manipulators. One needs to know the geometric nature of the LSS that are expected to occur, and in what frequency ranges. Forcing techniques can then be designed to produce flow perturbations that will be amplified by, or negate the naturally occurring LSS, depending on the desired outcome. This article will discuss some of the LSS studied at the Vortex Fluid Dynamics Lab (VFDL) using various flow visualization techniques, and the effect that open loop control methods have been shown to have. The flows discussed are: synthetic jet control of a jet in cross-flow, inadvertent pulsation influence on orifice plate flow meters, and another type of synthetic jet we call the "synthetic fence jet".

**Keywords:** *vortex dynamics, image correlation velocimetry, jet in cross-flow, vortex rings, synthetic jets*

## 1. Introduction

Fifty years ago, on April 25<sup>th</sup> 1953, two young scientists published a paper in Nature which led to a revolution in the life sciences: genetic engineering, genetic fingerprinting, gene therapy, the human genome project. The paper presented the structure of DNA and the researchers were Francis Crick and James Watson. In the pursuit of this elegant double helix structure, one of the critical pieces of information they used was the clearest X-ray image of crystallized DNA that anyone had ever obtained. Rosalind Franklin achieved this. Visualization was an essential link in building their model of the structure. From the X-ray they knew it was a helix, and the length of one helical turn within it [1]. In a similar fashion, visualization plays an essential role in turbulent large-scale structure (LSS) research. In a parallel to the DNA research, knowledge of the structure is allowing the emergence of new control techniques to interact with turbulent flows in innovative ways. How far this will go will be known only in the future, but rewards similar to the DNA case are not unimaginable.

A paradigm shift in turbulence research has suggested that turbulence may be described as the birth, evolution, interaction and decay of large-scale vortex structures [2]. This revolution was largely championed by my Ph.D. advisor Prof. Anatol Roshko and his lab at Caltech. If looked at in appropriate ways, these "orderly" structures can often be identified within the apparent chaos of

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turbulence. It is often the chaos which is more easily apparent. Knowledge of the vortex dynamics of these structures allows both the design of methods to influence the flow properties to the engineer's advantage [3,4,5], and the understanding of the effect of unsteady excitation [6,7,8,9,10,11]. Flow control can be achieved via unsteady mechanisms such as sound, moving control surfaces and micro-electro-mechanical-systems (MEMS), either directly or from the production of synthetic jets.

It is now generally accepted, since Brown and Roshko in 1974 [12], that most turbulent shear flows have characteristic large-scale vortex structures within them. Attempts at controlling a turbulent flow lead to better understanding of the vortex structures in that flow. Studying the structures allows the design of better flow control devices. Structure and control therefore have a synergistic relationship that feeds into and off of each other. Structure-knowledge and forcing-control are symbiotic. As a result, my basic philosophy of approach is to study both. We seek refined fundamental understanding of vortex structure dynamics, turbulence and ultimately flow control. I have created the Vortex Fluid Dynamics Laboratory (VFDL) at the University of Alberta. to contribute to these endeavours. Application areas of interest include improvements in mixing of pollutants, enhanced combustion efficiency that reduces greenhouse gas emissions, and drag reduction on vehicles or within pipelines. The expected significance of flow control is immense. A recent book on flow control [5] states: "The potential benefits of realizing efficient flow-control systems range from saving billions of dollars in fuel cost for land, air and sea vehicles to achieving economically and environmentally more competitive industrial processes involving fluid flows".

This article will discuss some of the LSS studied at the Vortex Fluid Dynamics Lab and the effect that simple open loop control methods have been shown to have. It is an update of an earlier companion article [13], with more emphasis on flow control than the former article.

### 2. Control of a Jet in a Cross-Flow (JICF) Using an Annular Synthetic Jet

This was originally posed as an attempt to control smoke-stack downwash by using acoustics or some form of synthetic jet. However, the flow geometry is essentially a type of jet in cross-flow (JICF) which has many other practical applications of importance: combustion chambers, aircraft aerodynamic control, and sour gas flare stacks in the oil and gas industry. We have found a control method that uses a vertically oriented annular synthetic jet deployed at the stack tip. It reduces the amount of downwash that brings potentially toxic emissions dangerously close to the ground, which poses a health risk for bystanders. This forcing technique is similar to a technique I used previously to control a separation bubble [6].

A synthetic jet [14] is a jet created from an actuating device that may be quite small. It consists of a cavity of oscillating volume, with an orifice on one side. The volume oscillations produce a succession of vortex rings from ambient fluid external to the device. When done properly, the rings form a jet although there is zero net mass flux through the orifice..

My colleague John Diep and I investigated the viability of a number of flow control concepts quickly using a smoke-wire. What produced the best results was an annular synthetic jet directed upwards around the lip of the stack to enhance the vertical momentum of the plume. The primary advantage of doing this at the lip, rather than using a larger blower below to increase the speed everywhere within the pipe, is that there is no speed-cubed energy loss from friction with the stack walls over the entire stack height. We also tried synthetic jets on a downstream vertical portion of the stack to reduce separation bubble size, but this only increased the downwash. Other hoped for methods of acoustic control were unsuccessful.

Flow visualization was also done with a bulk smoke system. In order to eliminate possible buoyancy effects the bulk smoke that is used for trajectory measurements is cooled to room

temperature in a plenum before being introduced to the smoke-stack. For the forcing, we used a powerful B+K Shaker Table Driver to push a piston that produced an oscillating flow through a long, stack-concentric annular channel from outside the wind tunnel to the stack exit plane. In a full-scale application, it would be done with a device simply attached to the end of the stack. This produces an annular synthetic jet concentric to the stack plume exit. For smaller JICF, this would be done with microactuators situated there.

Results for a laminar pipe flow exiting the stack is shown in Fig 1, portions of which are in [8, 9, 10]. The figure contains a montage of black and white images that have been digitally colorized. Beyond proving that downwash could be reduced by using a synthetic jet, we showed that the influence on the plume trajectory could be modelled by accounting for the additional vertical momentum it provided [10]. One significant result became apparent for low Reynolds number plumes. For a fixed forcing frequency, as amplitude of synthetic jet velocity was increased a *relaminarization of the plume occurred*. The previously dominating vortex structures that occurred with no forcing were completely erased. Calm parallel streamlines were evident in a separation bubble that appeared behind the stack. This is a very unexpected result: in some cases *increasing forcing amplitude can actually create less mixing*. As the amplitude of forcing was increased, the structures returned but locked to the forcing frequency. Turbulent mixing resumed and the plume rose higher as would be expected from the vertical momentum added by the annular synthetic jet. However there was another surprise in that a sudden transition of the vortex structures occurred at one amplitude. It was bistable; it would flip back and forth without adjusting the amplitude control knob at all.

### 3. Inadvertent Control of Orifice Plate Flows

The vortex ring is the simplest three-dimensional LSS possible: a line vortex closed on itself. The VFDL has done considerable work in the area of vortex ring creation and early evolution. We have studied the formation of vortex rings primarily in water drops impacting on, and bursting soap bubbles resting on, the surface of a pool. There is a remarkable similarity between the resulting three-dimensional vortex structures and an atomic bomb mushroom cloud as can be seen in Fig. 2 (from [13]). A series of vortex rings resonating with an imposed forcing can have an undesirable effect on a ubiquitous measurement device, the orifice plate flow meter. This inadvertent flow control will be discussed here.

There are over 100,000 orifice plate flow meters currently being used in North America. These meters are calibrated to calculate the volume flow-rate as a function of the measured pressure drop across the obstruction that the orifice presents to the pipe flow. It is assumed that velocity fluctuations (pulsations) or other unsteadiness in the turbulent pipe flow is small enough to have negligible effect. However, as their amplitudes rise they can create inaccuracies by interacting with the LSS downstream of the orifice plate. This is essentially an unintended control of the flow. Characteristic instabilities that have been previously found in shear flows, jet flows and reattaching flows [6] also exist downstream of the plate [11]. Smoke-wire flow visualization and LSS theory were used to develop a complete understanding of the flow physics [7].

The VFDL Pulsating Pipe Facility was designed and built by Dallas Chapple and myself to include a “see through” acrylic orifice plate and pipe, fully turbulent pipe flow, smoke-wire flow visualization, independent pulsation level control, and computer control and data acquisition. Analysis of photographs such as shown in Fig. 3 and 4 immediately suggest a cause for flow-rate measurement error. When the pulsation frequency corresponds to the jet “preferred mode” or shedding instability [6] frequencies found in separation bubbles, the vortices just downstream of the orifice begin to resonate with the forcing, Fig. 4. This narrows the vena contracta compared to no pulsation in Fig. 3, reduces the downstream pressure and therefore increases the measured pressure drop for the same flow rate. An overprediction error of as much as 40% occurs when the highest levels of pulsation were present. The converse can also occur, resulting in a much smaller

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under-prediction for a different and narrower frequency range. Meter installation designers can now avoid these dangerous pulsation frequencies to minimize error.

### 4. Synthetic Fence Jets

In the VFDL Pulsating Pipe Facility, Chris Apps and I attempted to create a jet coming off a flat plate fence obstruction placed in the pipe, as a potentially new type of actuator for flow control [15, 16]. For this experiment, there was no bulk pipe flow, only the acoustic standing wave that was used to provide pulsation. Our vortex dynamics arguments suggested that an acoustic velocity oscillation orthogonal to the fence could create a jet in the plane of the fence, radially inward to the pipe centre. Using smoke-wire streakline visualization, we proved that this was so. An example can be seen in Fig. 5a. We named it the Synthetic Fence Jet (SFJ), because it essentially synthesizes a jet from ambient fluid interacting with the fence. An interesting result is that the SFJ can be vectored up or downstream, *depending on the shape of the acoustic standing waveform in the pipe*. We pursued the SFJ idea for its value as an actuator that could be used in mixing chambers, or pipelines, but it also provides a possible explanation for a type of orifice plate meter error. At times, even if there is no net flow in the pipe, pulsation can create a pressure differential that indicates there is a flow.

We characterized the efficiency of conversion of acoustic velocity amplitude to resulting SFJ velocity. In order to measure the complex three-dimensional and unsteady flow that results in the creation of the SFJ, we needed a method of velocity measurement. Standard particle image velocimetry (PIV) would not work because the flow had a strong acoustic velocity component orthogonal to the jet flow. We therefore developed a form of image correlation velocimetry (ICV) based on the smoke-wire streaklines that we were photographing to visualize the jet. Using two time-delayed strobes of different colour and digital image processing, we were able to estimate the jet velocity with the help of Tony Chen [17]. Fig. 5a is actually one of these double-exposed images with a red and blue strobe flash. The advantage of this technique is that individual particles do not need to be imaged, any textured scalar tracer image will do, such as the smoke streaklines. Fig. 5b shows the result for the SFJ. An advantage of this technique is that it makes use of the visualization results that are frequently pursued for their vortex structural information. The addition of another light source of different colour allows an estimate of the velocity field as well.

### 5. Conclusions

Some of the research using visualization at the Vortex Fluid Dynamics Lab of the University of Alberta has been discussed. Open loop flow control can reduce bluff body drag [6] and usually increases mixing, but sometimes it can actually *decrease* mixing. It is remarkable what can be discovered quickly using fairly basic flow visualization techniques. Researchers are limited only by their creativity and care in interpreting the results. As flow visualization steadily increases our understanding of turbulent large-scale structures and their control, the future holds unimaginable benefits in the form of flow prediction and advantageous flow modification.

### Acknowledgments

As well as my colleagues mentioned within the text, appreciation is extended to Andrew Coward, Michelle Vigeant, Ian Buttar, Bernie Faulkner, Terry Nord, Dave Pape, Albert Yuen and Don Fuhr. Godfrey Mungal is thanked for the inspiration for the Fig. 1 colourization. This work was supported by the Natural Sciences and Engineering Research Council of Canada Grant OGP41747 and Nova Gas Transmission Ltd.

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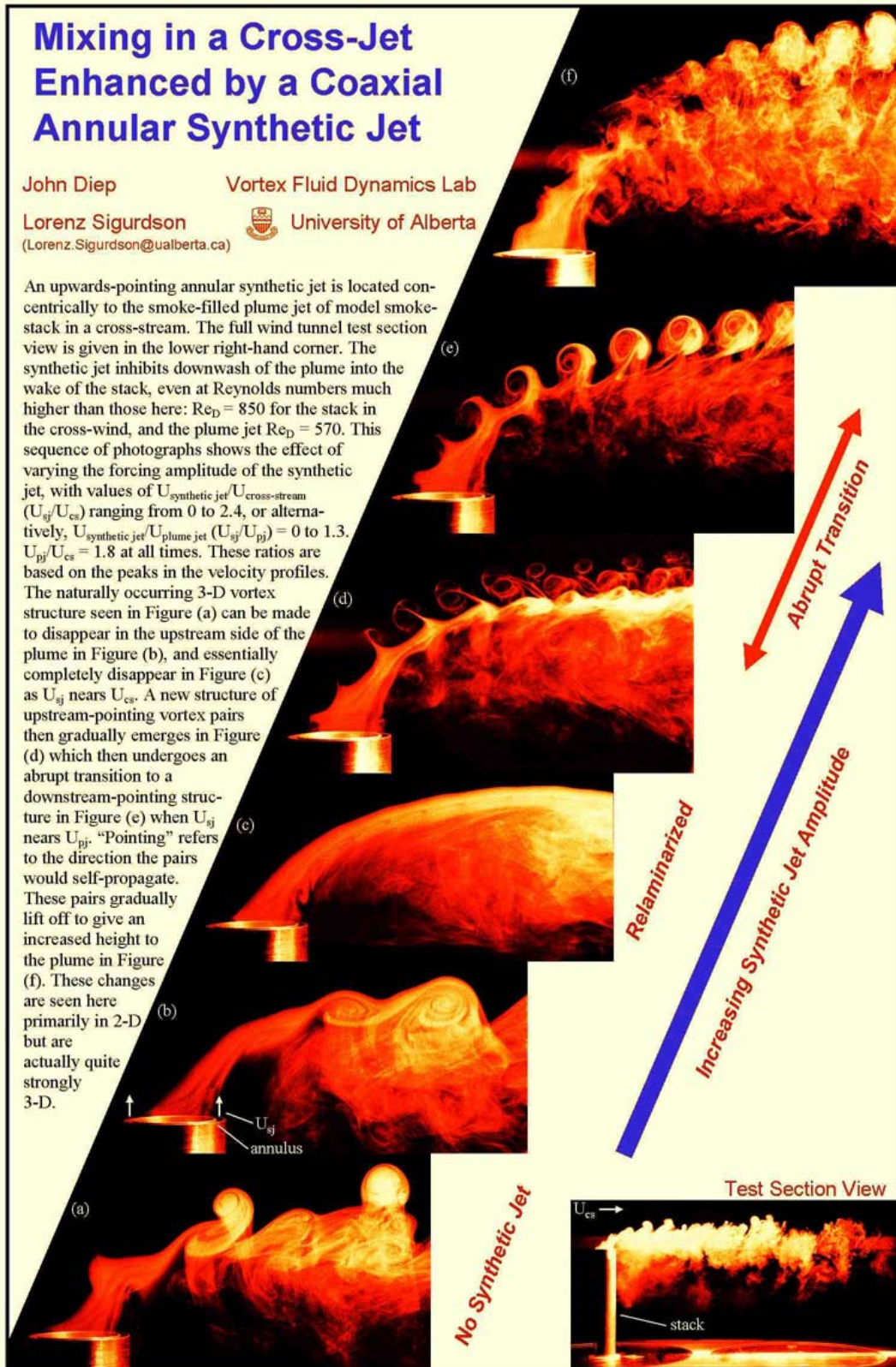


Fig. 1. Mixing in a cross-jet enhanced by a coaxial annular synthetic jet, Diep and Sigurdson [8,9,10]. Coloured smoke tracer.

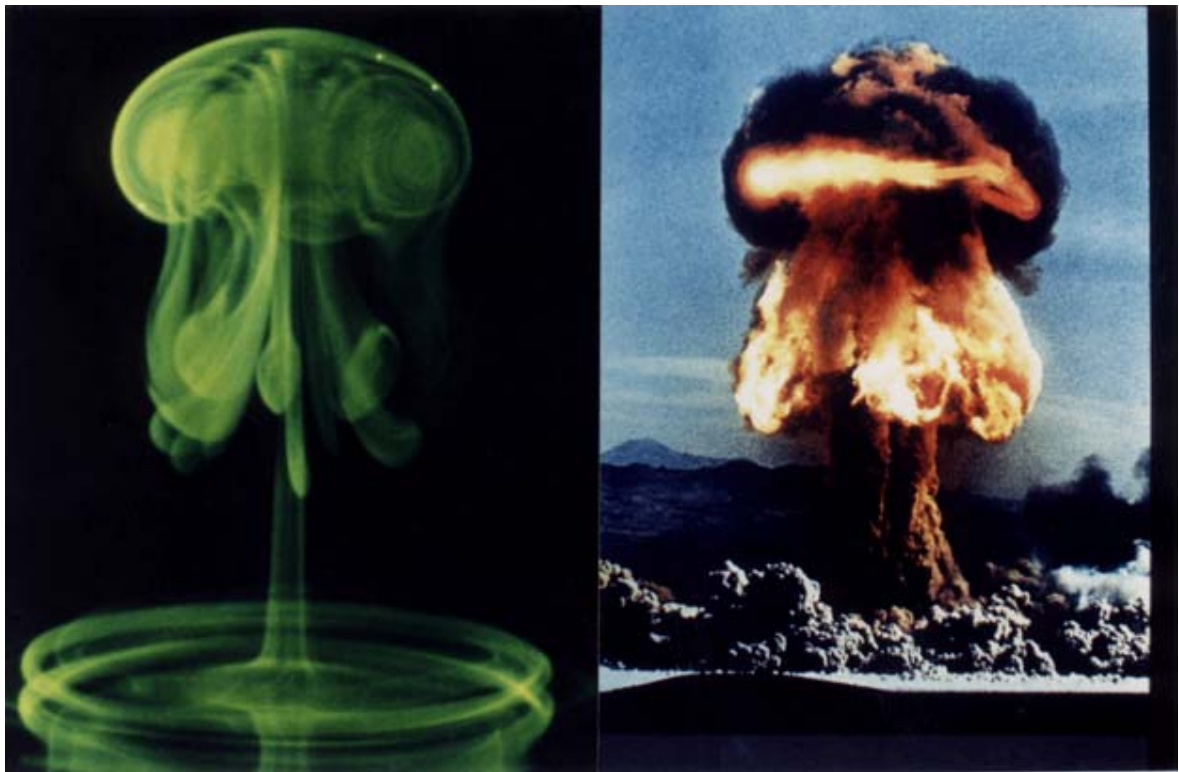


Fig. 2. Similarity in large-scale vortex structure of a dye-stained impacting water drop (inverted, left), and an above ground nuclear test (right, courtesy of the U.S. Dept. of Energy) from Sigurdson [13]. The drop photo is from: Peck, Bill and Sigurdson, L.W., Phys. Fluids, 6 [2] [Part 1], (1994), pp 564-578.

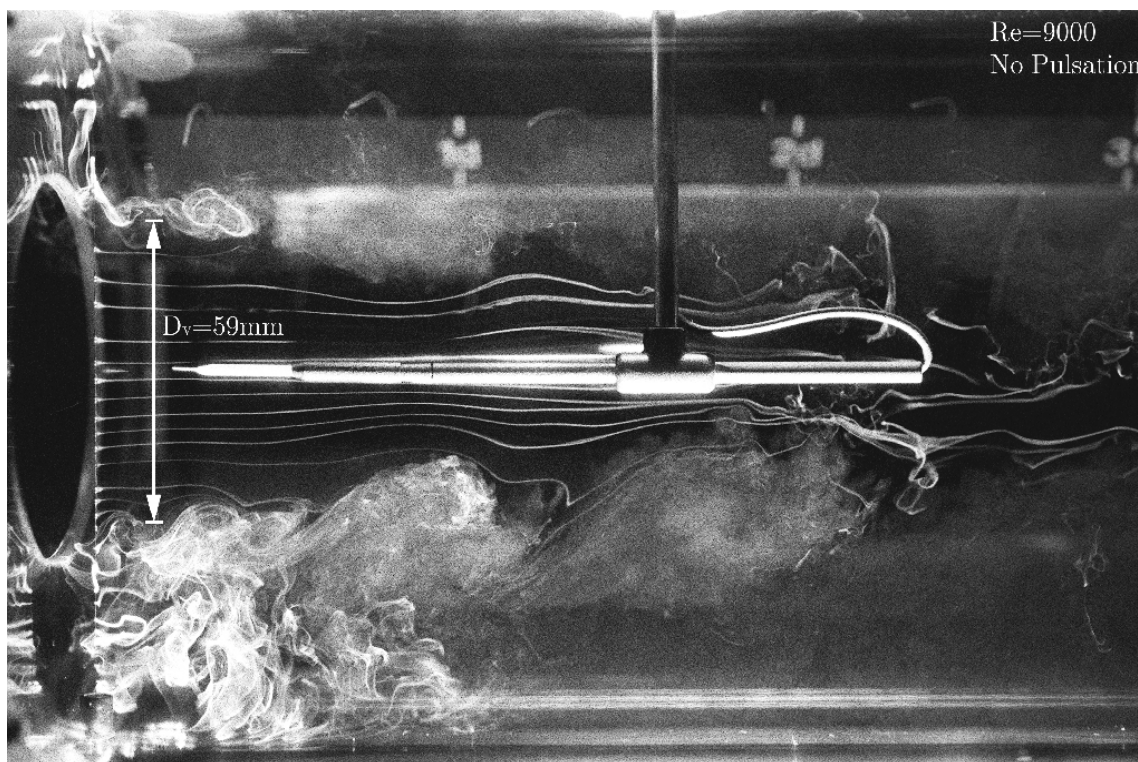


Fig. 3. Smoke-wire streakline photograph of orifice plate flow meter with no pulsation present, Reynolds number = 9000.  $D_v$  indicates the estimated vena contracta diameter. From Sigurdson and Chapple [7].

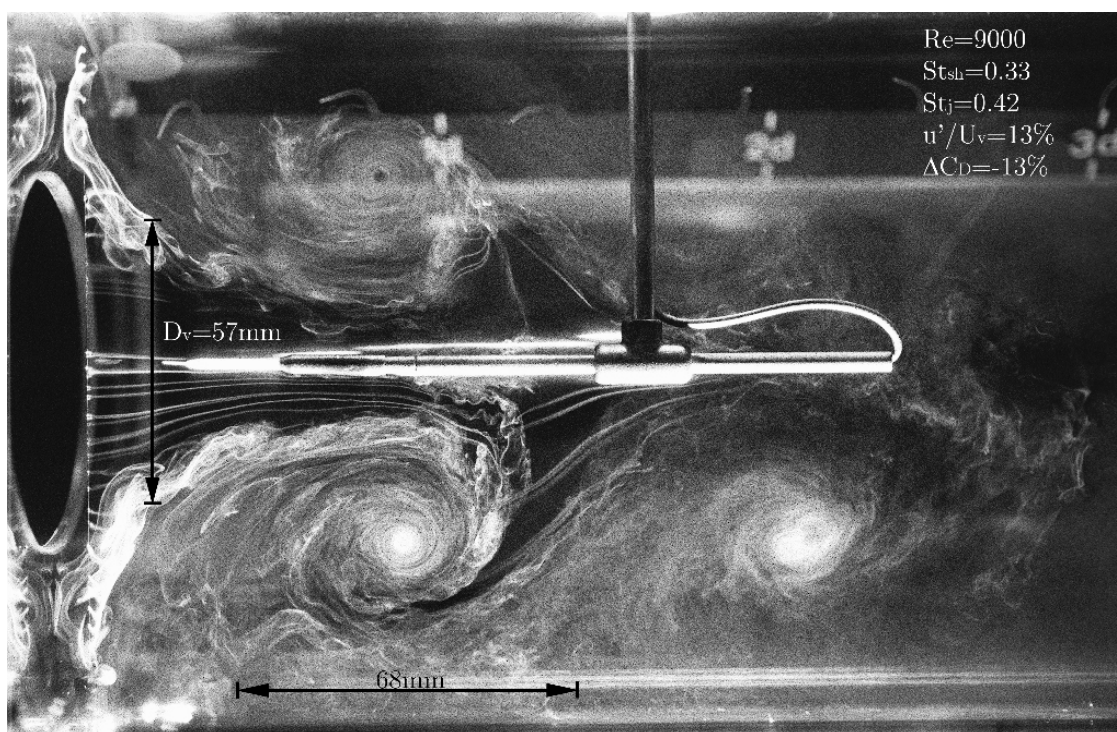


Fig. 4. Smoke-wire streakline photograph of orifice plate flow meter with pulsation present, showing a large effect. Reynolds number = 9000. The vena contracta diameter  $D_v$  is reduced from the no pulsation case. From Sigurdson and Chapple [7].

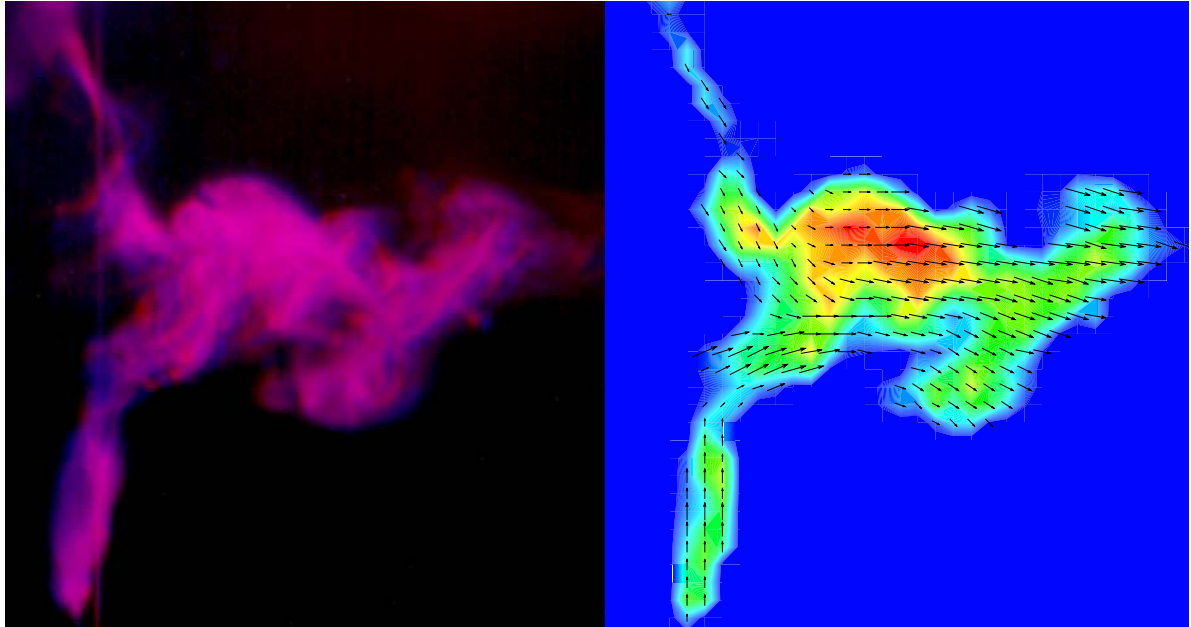


Fig. 5. ICV photograph and result for SFJ.

5a) [Above left] The cropped photograph of the SFJ. The approximate direction of view is along the pipe axis, orthogonal to the vertically oriented fence. The smoke-wire is parallel to the fence edge. 5b) [Above right] The velocity field calculated from the double exposure in Fig. 4a using ICV. After Apps [16], Apps, Chen and Sigurdson [17].