The application of PIV to the study of unsteady gas dynamic flow within pipes and at pipe discontinuities

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Abstract. This paper describes research using a pulse generator that provides discrete waves. The wave motion was recorded using a series of high speed pressure transducers and the ensuing movement of the gas particles within the pipes was recorded using digital PIV. Gas particle velocities of up to 250m/s were a regular occurrence and vortices of high angular velocity were a common problem with associated spin out of seed particles. Although flows were predominantly two dimensional, stereoscopic techniques were used to give optical access to otherwise inaccessible areas of flow. So far these techniques have been applied to the unsteady gas dynamic flow within plain pipes, at sudden expansions and contractions within pipes and at the end of a pipe open to the environment, both plain ended and when fitted with a bellmouth. Examples of all of these are presented in this paper.

1. Introduction
The performance and fuel economy of the internal combustion engine is heavily influenced by the unsteady gas dynamic flow processes that take place in any engine’s intake and exhaust system. These are predominantly the consequence of cylinder blowdown. Mathematical modelling of unsteady gas dynamics is essential to adequately predict how an engine will perform. Traditionally these models were based on one-dimensional gas dynamic methods such as those provided by the method of characteristics [1, 2]. These methods are slowly being replaced by the complete three-dimensional CFD simulation of the internal combustion engine from the air entering the engines intake to that exiting its exhaust [3, 4]. The accuracy of all of these techniques is dependant on validation against precisely acquired experimental data. To avoid the need to take into account the influence of combustion it is common practice to synthesize representative pressure and rarefaction waves using a pulse generator rather than a firing engine. These may produce a continuous sequence of waves or may be used to generate single waves that are fired into a quiescent pipe system.

As waves are reflected from pipe discontinuities the gas particle motion at any point along a pipe will be the consequence of the superposition of oppositely moving waves. For experimental research this can make life difficult, especially as the traditional means of observing pressure waves has been by using pressure transducers. These are unable to differentiate between oppositely moving waves, recording only the superposition pressure trace. However, if it is arranged that a single wave is fired into a pipe and the wave is able to fully pass the point of observation before it is reflected from a discontinuity then, ignoring a small contribution due to friction, the pressure trace will correspond to that of the incident wave only. The apparatus to generate discrete pressure and rarefaction waves is generally described as a single-shot apparatus. The evolution of such apparatus is described by Thornhill et al [5].
2. Overview of apparatus

A schematic of the most elementary configuration of the apparatus used for the current work is provided in Figure 1. The apparatus comprises a flow loop of approximately 12m length. The pressure wave generating device is to the right of the centre in the upper loop. A transparent test section forms the upper part of the loop to the left of the wave generating device. A variable speed fan is included in the lower loop to generate a background flow to keep seed particles in suspension. The remainder of the flow loop is manufactured from domestic waste pipe.

![Basic flow loop](image)

**Figure 1. Basic flow loop**

A composite section of a solid model of the pressure wave generating device is shown in Figure 2. Air from a pressurized chamber is released through the wall of the duct by opening a poppet valve in the top of the chamber. The valve is actuated via a finger rocker driven by a cam that acts on its roller follower. The cam is driven at a constant speed of 10 rev/second, and for most of its operation, the lobe that defines the valve’s movement passes to one side of the follower. Only when a pressure wave is required is the lobe driven sideways by a pneumatic cylinder so that it acts on the follower; see Figure 3. The instant the valve event is complete the lobe is once more displaced to the side. To allow consistent recharging of the pressurized chamber, valve events are scheduled to occur only once per minute.

Seed particles are introduced into the flow loop through a ‘rodding hole’ in one of the waste pipe bends. The particles are microscopic drops of olive oil generated using a TSI 6 jet atomizer with a claimed mean particle size of 0.6µm. Measurement of the particles before introduction into the flow loop revealed that typically the mean particle size was slightly over one micron diameter with a few particles up to 5µm diameter. Once introduced to the apparatus, the smaller particles are kept in suspension by using the fan to produce a gentle background flow. It was reasoned that the larger particles drop out of the flow at low air speeds. It was found that a flow speed of 0.25m/s in the return loop was the practical lowest speed that could hold an adequate density of particles in suspension for any length of time. This was calculated from the background flow velocity in the test section measured with the PIV.

Illumination for the PIV images was provided by a Spectra Physics PIV 200 dual pulsed Nd:YAG solid-state laser with an energy of 250mJ/pulse. The beam was transformed into a constant thickness light sheet of approximately 1.0mm thickness by three cylindrical lenses. The separation between pairs of laser pulses varied between 2 and 5 microseconds depending on the particle velocity being captured. As the pressure wave passes the interrogation region in approximately 7ms it is only possible to acquire one image pair from any one pressure wave.
3. Flow in a pipe

The development of flow in a pipe caused by the passage of a pressure wave was studied in a 3 m long transparent pipe of 28mm x 28mm square internal cross section. This was manufactured from 3mm thick acrylic sheet. The upper and lower walls were mortised to receive the side walls which were glued in place with chloroform.

A single PCO Sensicam was used to acquire images fitted with a 55mm Micro Nikkor lens set to an aperture of f8. Imaging of the particles close to the duct walls was spoilt by the perspective view of the walls in the background. In an effort to eliminate this from one wall, the camera was centred in line with that wall. This gave marginally better data close to this wall at the expense of the other.

The total interrogation area was 90mm long by 28 mm wide and was acquired at the mid plane of the pipe in line with its axis. It was divided into 79 x 25 overlapping regions of 32 x 32 pixels. Cross-correlation analysis of the images was performed using TSI Insight software.

The pressure history for each pressure wave was acquired using a 0-2 bar Kistler model 4045A piezoresistive transducer mounted flush with the pipe wall 85mm downstream from the centre of the PIV interrogation region so as to avoid it disturbing the flow. The transducer has a natural frequency of 20kHz. Amplification of the signal was by a Kistler model 4611 amplifier. The signal was captured at a frequency of 100kHz.

Figure 4 shows the rapid acceleration of the gas particles as the pressure wave first encroaches the interrogation region. The gas dynamic back calculated velocity is determined from the pressure trace recorded downstream of the interrogation region; a comprehensive explanation of this is provided by Thornhill et al [6]. A shock front has formed at the leading edge of the wave and the pressure transducer is unable to handle this adequately; its response is at first tardy and then it overshoots and oscillates briefly at its natural frequency.

It will be observed from the vector plot (a) that the gas particle velocity across the pipe at any section is very even. The peak and mean vector magnitudes at each section are provided by part (b) of
the figure. The near congruency of the two traces is again indicative of even flow across the pipe section.

Figure 5 shows the flow on a similar wave but about 3.1 ms after the passage of the shock front. By now the front of the wave will have travelled approximately 1 m past this point and each gas particle in the interrogation region will have travelled a little over 400 mm. The formation of a boundary layer is clearest at this point on the wave as later the velocity of the particles is retarding rapidly.

![Figure 4. Leading edge of steep fronted pressure wave (a) PIV vector plot; (b) mean and peak velocities.](image)

![Figure 5. Peak of a pressure wave (a) PIV vector plot; (b) mean and peak velocities.](image)

4. Flow at a sudden change in pipe area
Figure 6 shows the acrylic model used to study the flow at a sudden expansion and when reversed at a sudden contraction. The upstream pipe (to the right) is bolted rigidly to a heavily weighted stand and the downstream pipe is accurately aligned to this with shoulder screws passing through brass bushes. This arrangement allows the pipes to be separated and realigned accurately; necessary for cleaning and the positioning and removal of a calibration target.

![Figure 6. Sudden expansion](image)
The median plane of the two pipes was used for acquiring flow data both up and downstream of the area discontinuity. Stereoscopic PIV (SPIV) was necessary to see the flow actually at the area change due to the visual obstruction provided by the pipe flanges. Upstream and downstream flows had to be studied separately. Two PCO Sensicams were used, one above and one below the interrogation region, both set over at approximately 45º to it. 55mm Micro Nikkor lens were used, attached to the cameras via QUB designed Scheimpflug mounts.

Figures 7 and 8 show the flow downstream of the sudden expansion. Once more the pressure wave, which has a peak magnitude of 1.7 bar in the smaller upstream pipe, is steep fronted. This phenomenon is almost unavoidable on high magnitude finite amplitude pressure waves after they have travelled a few meters in a pipe at room temperature. In Figure 7 the steep front of the wave has travelled approximately 40mm from the increase in area. Vortices have formed to either side of the resulting jet but are poorly represented due partly to the relative sparsity of seed particles within these regions. Figure 8 shows a similar wave 0.32ms later. At this instant the wave front has exited the interrogation region and is approximately 80mm to its left. The vortex apparent in Figure 7 is again present but appears to have been joined by a second vortex 25mm further downstream. Other PIV images show that as the jet continues down the pipe it is still clearly apparent 300mm downstream, though it has expanded to fill ¾ of the width of the larger pipe.

Figure 7. SPIV vector plot of leading edge of steep fronted pressure wave after sudden pipe expansion (T= 5.31 ms).

Figure 8. SPIV vector plot of flow at exit to sudden expansion close to pressure wave peak (T= 5.63 ms).

Figures 9 and 10 show the flow upstream and downstream of a sudden contraction. Due to the large cross sectional area of the upstream pipe the pressure wave in this pipe only has peak magnitude of 1.22 bar and as a consequence will not form a steep wave front until well after the change in area. These images represent the wave close to its peak pressure and hence particle velocity. As the flow is well established by this point on the pressure wave there is evidence of a boundary layer both up and downstream of the contraction. A vena contracta is apparent in both figures. The sparsity of vectors in the smaller downstream pipe close to the area change is due to microscopic crazing of the acrylic pipe walls caused by excess chloroform applied to join the pipe to its flange.
5. Flow at the end of a pipe

In order to study the flow at open pipe ends a box was created that represents the environment surrounding the end of the pipe. This allowed the recirculation of seed particles to be continued as previously. The box and the wave generator are shown in Figure 12.

To investigate flow into bellmouths these were manufactured from aluminium alloy and black anodised. The light sheet is projected in from the end and to see deep into the each bellmouth SPIV is used with a camera set at 45° to either side of the light sheet. The cameras view the interrogation region through antireflection coated glass windows in the box walls. To maintain close up detail with the cameras at a distance of 800mm, 200mm Micro Nikkor lens were used inclined to the camera axis by 22.5° using our own design of Scheimpflug lens mount; Figure 11. The mount can be rotated to produce the Scheimpflug effect in any plane and rise and fall of the lens is also adjustable. This is necessary to prevent vignetting of the image at the back of the lens by the threaded C mount adaptor.
Figure 13 shows a cutaway view of a relatively small bellmouth attached to the end of an acrylic pipe of circular cross-section. The measured flow into the bellmouth caused by an incident rarefaction wave is illustrated in Figure 14. It was not possible to record vectors close to the walls of the bellmouth because of specular reflection of the light sheet. This was true with the bellmouth black anodised and also when painted matt black. The lack of vectors in the bottom right corner of the figure is due to masking by the near edge of the bellmouth.

Figures 15 and 16 were acquired using a single camera perpendicular to the presumed flow direction into or out of a pipe of circular cross section. This and the relative lack of optical obstruction has afforded images with vary few spurious or missing vectors.

**Figure 13.** Aluminum alloy bell mouth on Perspex pipe.

**Figure 14.** SPIV vector plot of flow into bell mouth due to incident rarefaction wave.

**Figure 15.** PIV vector plot of flow into square ended pipe due to incident rarefaction wave.

**Figure 16.** PIV vector plot of flow exiting square ended pipe just after arrival of steep fronted pressure wave.
Inflow to a square ended pipe caused by an incident rarefaction wave is illustrated in Figure 15. The lowest pressure on this wave was 0.8 bar. It is not steep fronted as rarefaction waves form their shock at their tails and generally have to travel many meters to do so. The lack of vectors at the corner of the pipe is once more due to specular reflection of the light sheet. The flow along the outside wall of the pipe towards the pipe end and the obvious convergence of the vectors as the flow enters the pipe demonstrate the advantage of attaching a bellmouth as seen previously in Figure 14.

The outflow from a square ended pipe subjected to an incident pressure wave is illustrated in Figure 16. The peak wave pressure was 1.5 bar and the wave was steep fronted as it was released from the pipe end. PIV vector detail in the vortices to either side of the jet are well maintained. Outflow from a bellmouth is almost identical with separation from the bellmouth wall occurring almost as soon as the flow area starts to increase.

6. Conclusions
This paper has illustrated some of the research being undertaken into unsteady gas dynamics using PIV and SPIV at Queens University Belfast. Studying internal flows at high velocities is difficult. The paper has concentrated on aspects of the work that will be of interest to other practitioners, highlighting problems as well as successes. Although not covered in this paper, the experimental work has been used to support the use of CFD in engine modelling; most of this has yet to be published. On the experimental front, much more work is still required.

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