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PULSE CONVERTERS IN NON-STEADY FLOW

by

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SUMMARY

A pulse converter is a simple device, which normally consists of three pipes, for preventing interference between cylinders in the exhaust system of diesel engines. Two simple theoretical models are presented for non-steady flow in a system with a pulse converter. The first model assumes a vortex switch which closes one pipe at the pulse converter and prevents back flow. The other model assumes that the pressures at each end of the three pipes in the pulse converter are equal and fully open to the flow. Dynamic experiments show that there is some back flow in the pulse converter in the closed pipe, and the predicted pressures do not agree with the theory for this regime, however, both the switched vortex theory and the branch theory give reasonable predictions of the pressure pulses in the initiating pipe for the blowdown and scavenge pulses from the cylinder connected to the pipe. Both theories also give reasonable predictions of the pressure pulses at the nozzle end of the pipe (representing a turbine). The switched vortex theory gives excellent predictions of air flow rates in the system.

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INTRODUCTION.

By fitting turbines in the exhaust systems of diesel engines to utilize the exhaust energy, it is possible to increase the specific output of engines. The turbines drive compressors which increase the air mass flow rate through the engine and hence the quantity of fuel which can be burnt. To obtain maximum utilisation of the exhaust gas energy, the exhaust pulse formed in the pipe at the commencement of the exhaust period should be conserved as the pressure wave passes down the pipe to the turbine. Application of modern gas dynamic theories to exhaust system design has made possible the development of efficient turbocharger systems. The main problem has been to conserve the pulse form without interference between cylinders during the gas exchange process. For certain groups of engine cylinders (4, 8, 10, etc.) this objective can only be achieved by providing separate paths to the turbine. Under these conditions the turbine is operating under partial admission with resultant loss in efficiency. A pulse converter is a device which enables a number of cylinder exhaust pipes to be grouped together to provide all round admission to the turbine without interference.

Originally the pulse converter was suggested as a method of converting the pulsating flow in the exhaust system to a constant pressure ahead of the turbine without the loss of the available energy in the pulse. Complex designs of nozzles and ejectors were suggested and made, but the device was not generally used (1). Later simplified designs were developed by Sulzer (2) which form the basis of the current form of pulse converter as shown in figure 1. It will be seen that the converter consists essentially of two tapered pipes entering a common outlet or mixing pipe. The critical dimensions are the inlet pipe area F_R, the mixing pipe cross-sectional area F_M, the narrowest cross-sectional area F_D and the length of the lip L. The optimum design parameters based on experiments suggested by Petak (2) are:

$$F_D = 0.5\ F_R$$

$$F_M = 0.5 \sum F_R$$

Nakada and Yumoto (3) have suggested that the lip length L is also a critical dimension.

A qualitative study of the action of a pulse converter, using a water table, was reported by Zehnder (4). The results are shown in figure 2. It will be seen that a pulse transmitted down one pipe A forms a vortex at the lip which fills the entry to the second pipe B and prevents flow along the pipe. The pulse converter thus acts as a pulse isolator or switch.

We can consider a pulse converter as a special type of pipe junction. Benson et al (5) have described two methods for studying non-steady flow in a system with pipe junctions. In both these methods the flow in the pipe is examined using one dimensional non-steady gas dynamics. At the pipe junction quasi steady flow models are used for the boundary conditions. In the first method the pressure at the end of each pipe at the junction is considered to be the same. This is called the constant pressure theory. In the second method the pressure losses at the pipe ends are determined experimentally and included in a momentum loss model. This is called the pressure loss theory. The constant pressure theory does not allow for the junction geometry except for the pipe areas at the junction, whilst the pressure loss theory depends on experimentally determined data. Both of these theories could be applied to the pulse converter. A third approach is to use the qualitative picture of Zehnder and to set up a model in which the switching operation could be included. In this case there would be simply a two pipe junction with the pipe communication depending on the pressure levels in the pulse converter.

In this paper calculations with the constant pressure theory and the switching model are presented. Since the completion of the work reported here, Watson and Janota (6), and Nakada and Yumoto (3), have presented results with the pressure loss theory.

THEORY.

The full treatment of non-steady flow in ducts has been presented elsewhere (7), (8), together with the numerical techniques to solve the basic equations. We use the variables

$$A = \frac{a}{a_{ref}}\ , \qquad U = \frac{u}{a_{ref}}\ , \qquad A_a = \frac{a_A}{a_{ref}}\ , \qquad Z = \frac{a_{ref}t}{L_{ref}}\ ,$$

$$X = \frac{x}{L_{ref}}\ , \qquad \lambda = A + \frac{k-1}{2}U\ , \quad \beta = A - \frac{k-1}{2}U\ ,$$

where a is the local speed of sound, u the particle velocity, a_A corresponds to an isentropic state change from a pressure p to a reference pressure p_{ref_1} (figure 3(a)), t is time, x is distance and a_{ref} and L_{ref} are reference speeds of sound and length.

The Z-X field is subdivided into a mesh system. The values of λ, β and A_a are calculated at each mesh point. The mesh proportions ΔZ : ΔX are selected based on stability criteria. At the boundaries, either λ, β or A_a are known and the boundary equations calculate the unknown values.

PULSE CONVERTER BOUNDARY CONDITIONS.

We will assume that the pressure at the end of each pipe at the junction is the same. We will consider two models for the pulse converter; the first a simple three-way branch, the second a two-way switch or switched vortex junction. The basic theory is the same for both models except that for the first model we consider all three pipes at the junction and for the second, only two pipes at a junction. We will outline the basic theory first in terms of the three-way junction.

The system is shown diagrammatically in figure 3(a) with the entropy diagram.

At the junction, we assume that:

$$p = p_1 = p_2 = p_3 \tag{1}$$

Furthermore, continuity of mass at the junction gives:

$$\sum \rho u F = 0 \tag{2}$$

We define the following parameters:

$$A^* = \frac{A}{A_a} = \left(\frac{p}{p_{ref}}\right)^{\frac{k-1}{2k}}\ , \ U = \frac{u}{A_a} \tag{3}$$

$$\lambda^*_{in} = A^* + \frac{k-1}{2}U^*\ , \ \lambda^*_{out} = A^* - \frac{k-1}{2}U^* \tag{4}$$

When gas flows across a junction there is an entropy change at the pipe end represented by: (A_{an}/A_{ac}). This causes a change in λ^*_{in} from $\lambda^*_{in.n}$ to $\lambda^*_{in.c}$ at the pipe end given by:

$$\lambda^*_{in.c} = A^* + \frac{A_{an}}{A_{ac}}\left(\lambda^*_{in.n} - A^*\right) \tag{5}$$

where A_{an} is the representative entropy before the gas enters the pipe, and A_{ac} the entropy of the incoming gas stream. At the pipe junction we can combine equations (1) and (2) with (3) and (4) to give:

$$A^* = \frac{\sum\left(\frac{F}{A_a}\right)\lambda^*_{in}}{\sum\left(\frac{F}{A_a}\right)} \tag{6}$$

and at each pipe end:

$$U^* = \frac{2}{k-1}\left(\lambda^*_{in} - A^*\right) \tag{7}$$

$$\lambda^*_{out} = A^* - \frac{k-1}{2} U^* \qquad (8)$$

Equations (5) to (8) define the boundary conditions at a junction.

THREE-WAY JUNCTION (Figure 3(b)).

In this case all three pipe ends are considered. The basic equations (5) to (8) are solved for F_1, F_2, F_3 where F_1 and F_2 correspond to F_D and F_3 to F_M. The tapered pipe from F_R to F_D is included in the one dimensional non-steady equations.

TWO-WAY SWITCH (Switched Vortex Junction (Figure 3(c)).

In this case, if $p_1 > p_2$ then the pipe end (2) is closed and we have flow from F_1 to F_3. If $p_2 > p_1$ then the pipe end (1) is closed and we have flow from F_2 to F_3. We use equations (5) to (8); but with only two pipes at a time corresponding to the switch. As before, F_1, F_2 corresponds to F_D and F_3 to F_M and the tapered pipe is included in the one dimensional non-steady equations.

EXPERIMENTAL INVESTIGATION.

A number of experiments were carried out to test the pulse converter under simulated engine conditions and to compare the results with the two theories. The engine gas exchange system was simulated in the apparatus shown in figure 4. This comprised a number of cylinders, of constant volume, (up to 6) with cylinder heads. In each cylinder there were two heads. A lower head in which high and low pressure air was supplied to the cylinder through timed valves, and an upper head in which the conventional exhaust valve was fitted. The pulse converter (figure 1) was made of perspex and fitted into the exhaust system (figure 4). A nozzle was fitted at the outlet end of the exhaust system to simulate a turbine.

The cycle of events were:

(1) High pressure air admitted to represent the cylinder gases.

(2) Exhaust valve opened and high pressure air discharged to exhaust system.

(3) Low pressure air admitted into cylinder to represent the scavenge air to simulate the charging process.

(4) Exhaust valves closed followed by closure of low pressure air valve.

The two camshafts were driven by a variable speed drive. In the experiments reported here the camshafts speeds were 218 to 637 r.p.m., with release pressures from 3.4 to 5.9 bar. Tests were carried out with two and four cylinder combinations. A summary of the two cylinder tests is given in Table 1.

The air flow rates were measured in the intake manifolds (figure 4). Transient pressures were recorded in the pulse converter and at the nozzle end of the exhaust pipe as well as in the cylinder.

Typical transducer records are shown in figure 5. The air flow measurements are given in Table 1.

DISCUSSION OF RESULTS.

All nine tests with the two cylinder combinations gave similar results. In figure 5, typical results (full line) are shown for test 3. It will be seen that at each entry point to the converter there are two primary pulses P1 and P2 and two secondary pulses S_1 and S_2. The primary pulses are due to the initial blowdown and the secondary pulses to the scavenge air. At entry 1 the pulses from cylinder 1, P1 and S_1 are of greater magnitude than the corresponding pulses from cylinder 2, P2 and S_2. At the pulse converter exit the primary pulses P1 and P2 are approximately of the same magnitude, similarly the secondary pulses S_1 and S_2 are approximately the same. At the nozzle the same comment holds although the magnitudes of both sets of pulses increase due to reflection at the nozzle end of the pipe. Thus, it is clear that there is some attenuation of the "back flow" along the pulse converter pipe in which there is nominally no flow. Therefore, the switched vortex theory does not appear to hold for the dynamic conditions in an exhaust system and there must be some back flow.

The calculations using switched vortex theory (broken line), however, agree favourably for the primary and secondary pulses when there is flow in the pipe. However, the switched vortex theory shows no pulses in the so called closed pipe. The three-way branch theory (chain line) gives reasonable agreement for the primary and secondary pulses in the pipe initiating the flow, but there is poor agreement for the closed pipe. When examining the pressure at the nozzle end of the pipe the switched vortex theory gives slightly better results than the three-way branch, but both theories are quite good. Despite the discrepancy in the pressure predictions the air flow predictions are remarkably good (Table 1). Here the switched vortex model gives better results than the three-way branch model.

We may conclude from these experiments that, whilst general qualitative trends may be predicted using the two simple theories for the pulse converter, exact predictions of the back flow are poor. On the other hand, predictions of the pulse form at the nozzle end of the pipe, representing the turbine, are quite good and the air flow predictions are excellent. Thus the methods outlined can assist towards optimization of the pulse converter form. For exact predictions the uses of loss coefficients as suggested by Benson et al (5) for branch flows must be allowed for in the calculations. Recently Watson and Janota (6) have applied these methods with success.

CONCLUSIONS.

Dynamic experiments with a pulse converter show that simple models for the flow can give reasonable predictions of the primary and secondary pulses in the pipe initiating the flow but not in the closed pipe. The experiments indicate that there is some back flow from the main stream into the closed pipe. The simple models, however, give good predictions of the pressure forms at the nozzle end of a pipe (representing a turbine) and the simple switched vortex gives excellent results for the prediction of air flow rate.

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TABLE 1

EXPERIMENTAL AND COMPUTED RESULTS

Test No.	CYLINDER 1		CYLINDER 2		R.P.M.	Experimental Mass Flow (kg/s)	SWITCHED VORTEX THEORY		THREE-WAY JUNCTION THEORY	
	Release Pressure bar	Release Temp. ^{o}K	Release Pressure bar	Release Temp. ^{o}K			Mass Flow (kg/s)	Difference Between Computed and Experimental Mass Flow %	Mass Flow (kg/s)	Difference Between Computed and Experimental Mass Flow %
1	3.883	328.9	3.503	327.8	218	0.0336	0.0334	- 0.2	0.0358	+ 6.6
2	5.359	333.9	4.869	332.2	218	0.0387	0.0386	- 0.1	0.0414	+ 6.9
3	6.924	338.9	6.317	337.2	217	0.0434	0.0439	+ 1.1	0.0470	+ 8.2
4	4.089	329.4	3.683	328.3	422	0.0422	0.0420	- 0.4	0.0453	+ 7.5
5	5.345	333.9	4.917	332.2	422	0.0479	0.0495	+ 3.4	0.0525	+ 9.6
6	6.634	338.3	6.179	336.7	429	0.0542	0.0565	+ 4.3	0.0596	+10.0
7	3.931	328.3	3.407	327.2	643	0.0444	0.0456	+ 2.8	0.0481	+ 8.5
8	5.476	334.4	4.841	332.2	647	0.0550	0.0567	+ 3.2	0.0600	+ 9.2
9	6.890	338.9	6.200	336.7	637	0.0637	0.0636	- 0.2	0.0675	+ 6.0

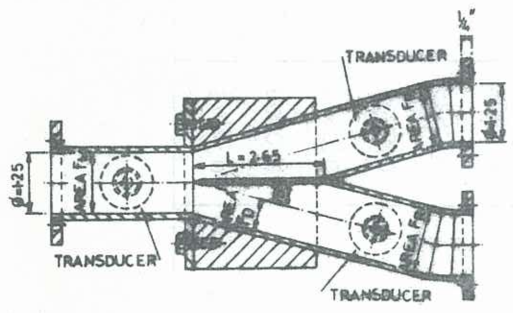
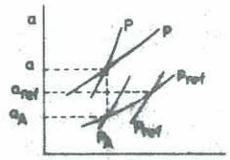
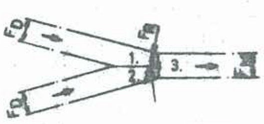


FIG.1. SULZER TYPE PULSE CONVERTER.



(a) ENTROPY DIAGRAM.



(b) THREE WAY JUNCTION.

(c) 'SWITCHED VORTEX' JUNCTION.

FIG. 3. THREE WAY JUNCTION & SWITCHED VORTEX.

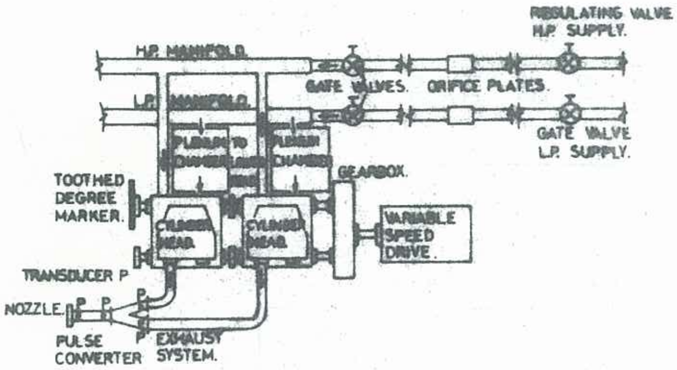


FIG. 4. DIAGRAMMATIC REPRESENTATION OF APPARATUS.

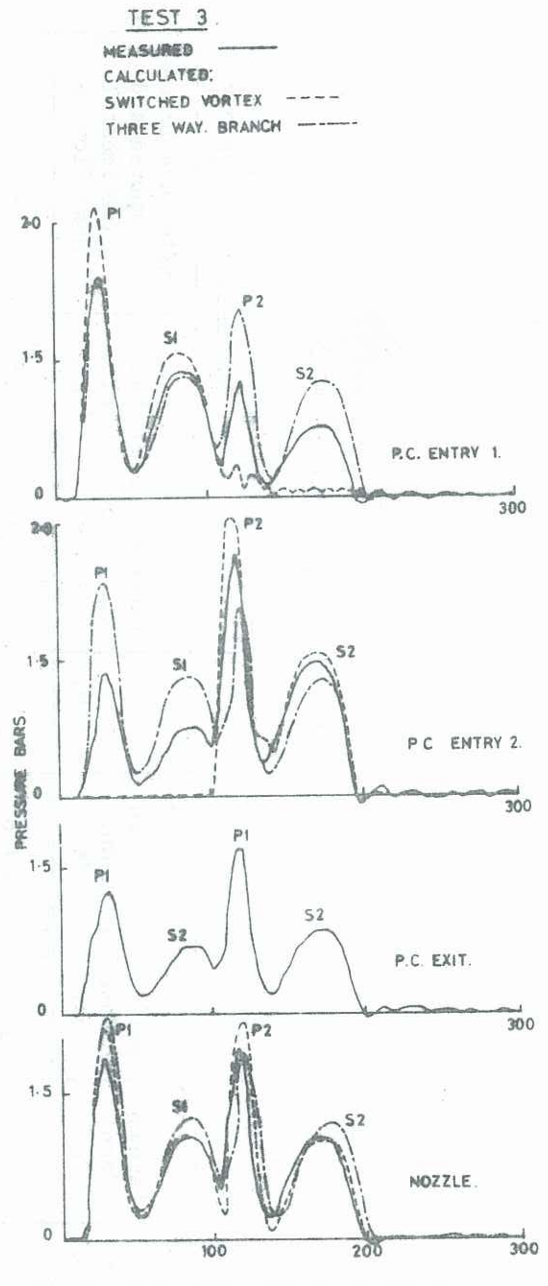


FIG. 5. COMPARISON OF MEASURED & CALCULATED TRANSIENT PRESSURES.

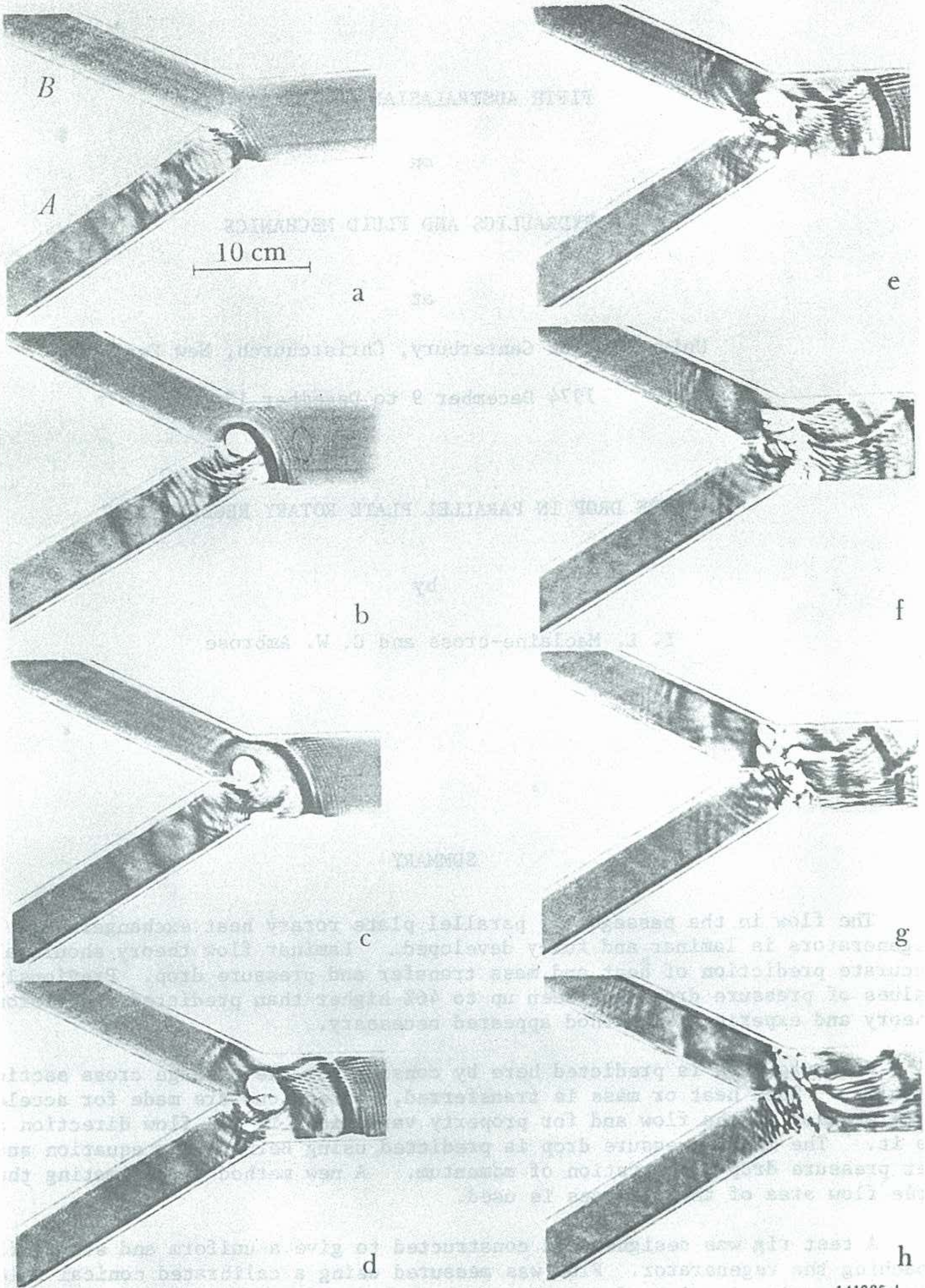


FIG. 2. WATER TABLE FLOW VISUALISATION OF PULSE CONVERTER JUNCTION.