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PERFORMANCE OF A TWIN-ENTRY AUTOMOTIVE TURBOCHARGER TURBINE

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ABSTRACT

Twin-entry radial flow turbines are commonly used in turbocharging vehicle diesel engines since they can take the best advantage of the pulse turbocharging technique. A wide experimental investigation was developed on a dedicated test rig in order to analyze steady and pulsating flow behavior of a twin-entry vaneless radial turbine.

Steady flow turbine performance was measured both with equal and unequal admission, highlighting the interactions between the two entries.

Unsteady flow tests were developed with controlled pressure pulse characteristics at each turbine entry. The influence of a phase difference between pulses at the two entries was also investigated: instantaneous pressure diagrams and averaged turbine performance are analyzed and compared in the paper.

NOMENCLATURE

Notations

c	gas velocity
f	frequency
n	rotational speed
t	time
p	pressure
u	rotor tip speed
A	cross sectional area
M	mass flow rate
R	centroid radius of cross sectional area
T	temperature, pulse period
ε	expansion ratio
η	efficiency
τ	torque
ϕ	phase difference angle
η'_t	$= \eta_t \cdot \eta_m$
Δ	amplitude

Subscripts

1	turbine inner entry (referred to the center housing)
2	turbine outer entry (referred to the center housing)
3	turbine inlet
4	turbine exit
eq	equivalent isentropic
m	mechanical
s	isentropic
t	turbine
R	reservoir
T	stagnation conditions

INTRODUCTION

Pulse turbocharging technique is widely used nowadays, especially in the field of vehicle diesel engines. The main goal is to take full advantage of the high pressure and temperature which exist in the cylinder when the exhaust valve (or port) opens, even at the expense of creating highly unsteady flow through the turbine. This system requires small-bore and small-volume manifolds, which give rise to sensible interferences between cylinders joined into one pipe. It is generally recognized that the best efficiencies are achieved by grouping three cylinders in one manifold, since

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in this case the quiescent period between pressure pulses is kept to a minimum while unfavorable interferences between cylinders are avoided (Watson and Janota, 1982). This technique allows a better scavenge process and an increased volumetric efficiency, especially at low engine speed and torque.

To separate pressure pulses in each manifold the resulting configuration of the exhaust system requires the use of a multiple-entry turbocharger turbine. Vaneless radial flow turbines for vehicle applications are usually fitted with two-entry casings, divided either meridionally (twin-entry type) or circumferentially. Meridionally divided casings are often used, since they allow for higher efficiencies over a wider operating range (Pischinger and Wunsche, 1977).

The flow characteristics (pressure, temperature, speed) at both turbine entries change continuously during the engine cycle. As a consequence, the turbocharger turbine instantaneously operates in partial or unequal admission conditions. Moreover, depending on the number of engine cylinders connected to each manifold and on the firing order, pressure pulses at the turbine entries are not likely to be in phase.

The knowledge of turbine performance under these operating conditions is very useful to improve turbocharger matching and to achieve a better understanding of the exhaust system behavior. Since in the open literature little detailed performance data are available for radial twin-entry turbines (Watson and Janota, 1982; Dale and Watson, 1986), theoretical and experimental investigations are required in this field.

Testing a twin-entry turbocharger turbine needs a suitable experimental facility that allows independent control of admission conditions for each entry, both in steady and in pulsating flow. This paper describes the results of a broad experimental investigation on an automotive twin-entry turbocharger turbine developed on the facility of the Department of Energetic Engineering of the University of Genoa (DINE).

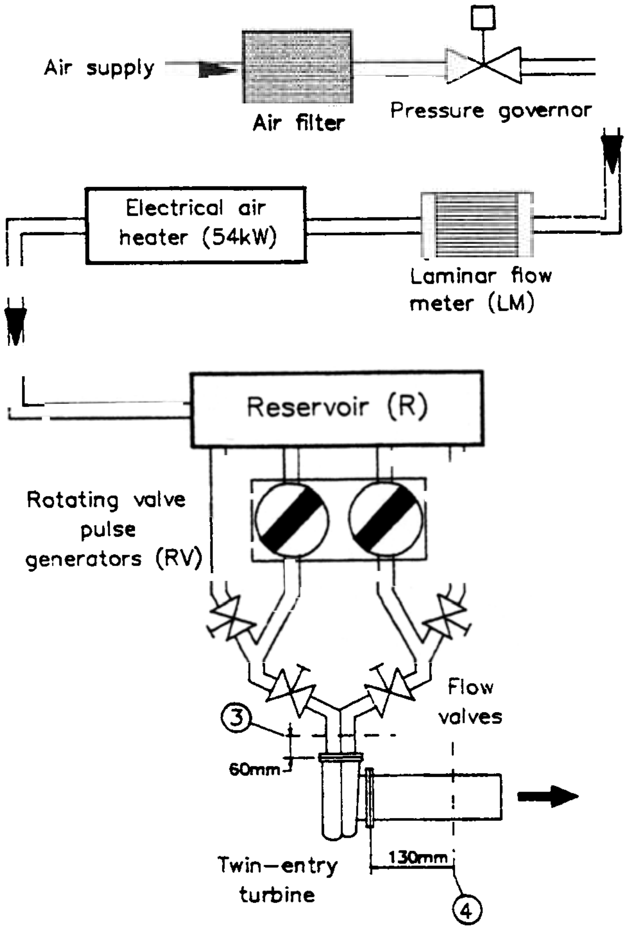

Fig. 1 *Arrangement of the turbine feeding line on the test facility.*

EXPERIMENTAL FACILITY AND TEST PROGRAM

The DINE test facility was initially developed to run tests on turbochargers, and then modified to allow measurements on different devices including complete intake and exhaust systems of automotive engines.

The facility layout was fully described in previous papers (Capobianco and Gambarotta, 1992). The main source of compressed air is three electrically-driven screw compressors, with a maximum delivery of about 0.65 kg/s at a maximum pressure of 8 bar. Two separate feeding lines with controlled air pressure levels are provided: in the case of tests on exhaust turbochargers one of them is dedicated to the turbocharger compressor, which is used as a dynamometer. Turbine power can be evaluated on the basis of measurements on the compressor side of the turbocharger. Controlling the compressor supply pressure and, therefore, its power absorption allows to extend considerably measured turbine operating range without the complexity and costs of a dedicated high-speed dynamometer. In the present investigation it was possible to cover a load range equivalent to blade-speed ratios u/c_s from 0.55 to 1.00.

The main supply line of the test facility was dedicated to the turbine. The experimental arrangement allows tests on two-entry turbines with full, partial or unequal admission, both in steady and pulsating flow conditions. The main characteristics of unsteady flow simulating the engine exhaust can be controlled independently for each turbine entry and the phase between the pressure pulses can be easily modified in steps of 1/10 of the pulse period. A schematic of the turbine feeding line is shown in Fig. 1. The pressure governor and the flow rate measuring station

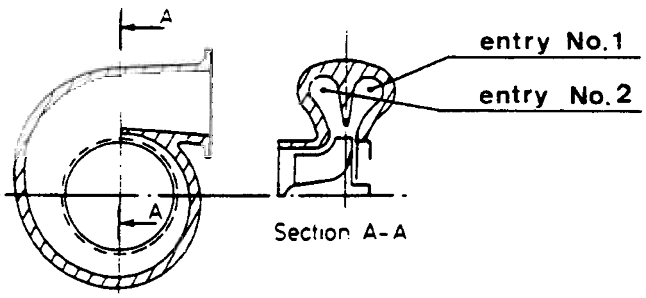

Fig. 2 - *Schematic of a twin-entry radial turbine.*

(fitted with a laminar flow meter LM) are followed by an air heater and a small reservoir R, which acts as damping element and flow distributor. In the case of unequal admission tests, a second laminar flow meter was installed upstream of one of the turbine entries to measure the relevant mass flow rate. However, this was not possible in pulsating flow conditions due to the damping effect of the laminar meter.

For each turbine entry two separate pipes are provided, in one of which a rotating valve (RV) generates pressure pulses. An effective control of pressure oscillation parameters at each turbine entry is obtained by mixing a steady flow component with a pulsating one. Dedicated valves allow regulation of the pulse characteristics (amplitude and mean value), while the flow area diagram of each pulse generator can be easily changed by replacing its rotor and stator ports. Pulse frequency can be adjusted in the typical range of inlet and exhaust systems of high-speed automotive engines (10 - 250 Hz).

An automatic data acquisition system (Capobianco and Gambarotta, 1992), controlled by an IBM-AT computer through a software developed by DINE, was used in the investigation. Average and transient pressures were measured by high frequency response strain-gauge transducers, while mean temperature levels were evaluated by

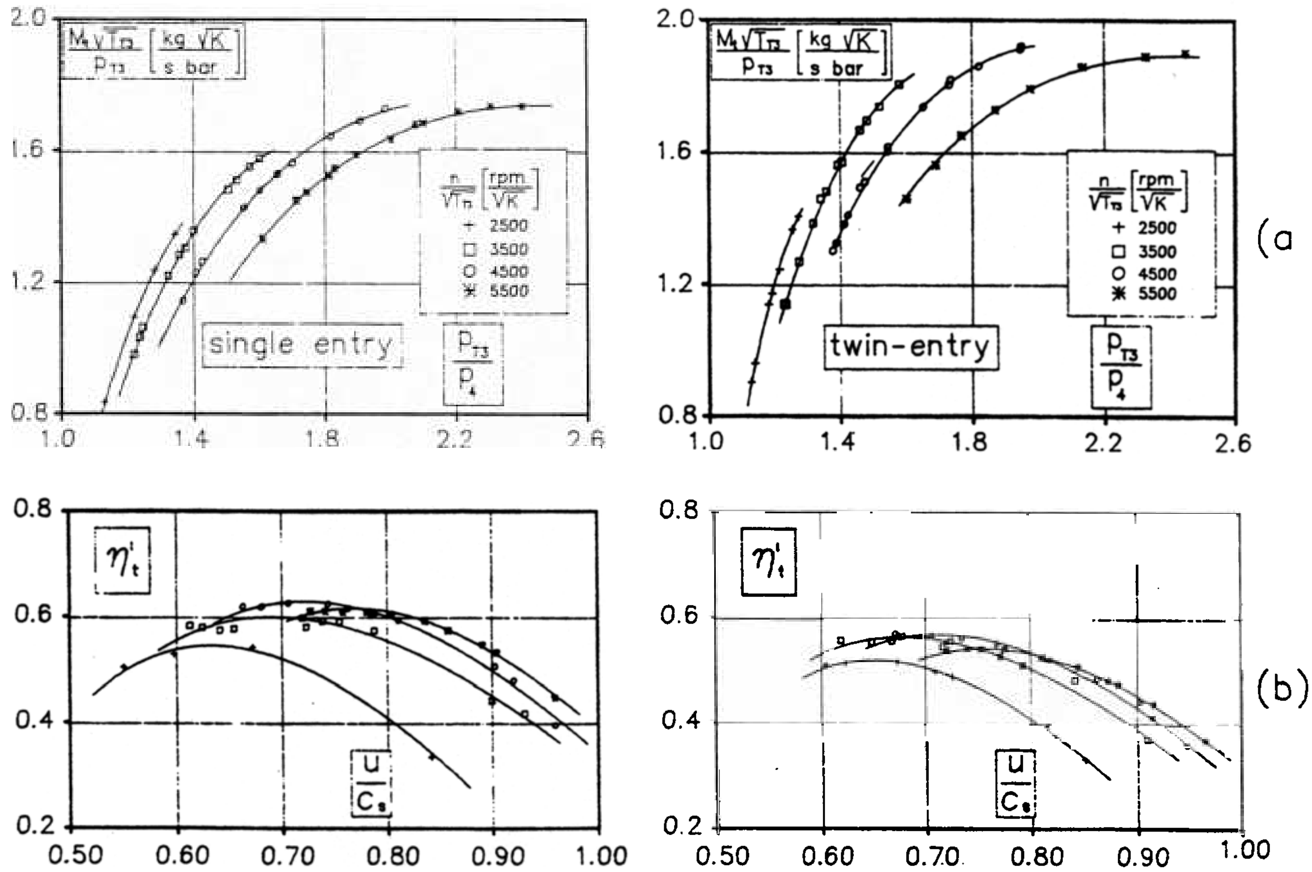

Fig. 3 - *Single and twin-entry (full admission) turbine mass flow (a) and efficiency (b) characteristics.*

platinum resistance thermometers. Turbocharger speed and rotating-valve frequency were measured by inductive probes. A sharp edged orifice was used to estimate the compressor mass flow rate.

The investigation was developed on a Garrett T025 automotive turbocharger, fitted with a twin-entry vaneless radial flow turbine. Referring to the meridionally divided turbine scroll, the inner portion (with reference to the turbocharger center housing) was designed as sector 1 (Fig. 2). Turbine aerodynamic parameters (i.e. rotor trim and housing A/R ratio) and, therefore, its swallowing capacity were similar to the fixed and variable geometry Garrett T025 turbines tested in former investigations (Capobianco et al., 1990; Capobianco and Gambarotta, 1992). No waste-gate valve was fitted on the twin-entry turbocharger.

The experimental program was extended both to steady and pulsating flow. Steady flow turbine performance was evaluated in full, partial and unequal admission conditions. The relevant results are discussed and compared with the few other available in the open literature.

Unsteady flow tests were developed to investigate the effects of a phase difference between pressure pulses at the turbine inlets, since this situation usually occurs in real operating conditions due to the firing order of the cylinders connected to each turbine entry. Measured pressure diagrams and average turbine performance are discussed and compared with those obtained with full and partial admission.

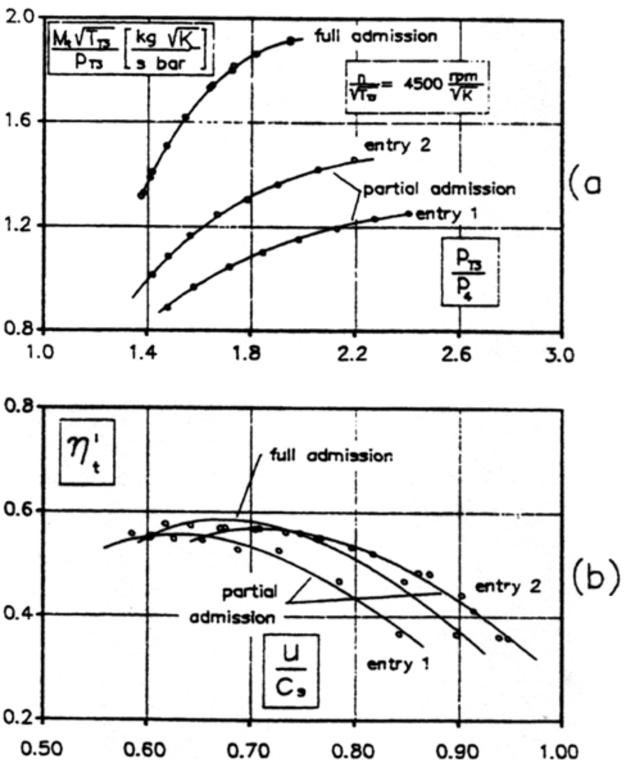

Fig. 4 - *Turbine mass flow (a) and efficiency (b) curves under full and partial admission.*

STEADY STATE MEASUREMENTS

Full and partial admission results

Steady flow turbine performance was determined with reference to four constant values of the non-dimensional rotational speed $n/\sqrt{T_{T3}}$, ranging from 2500 to 5500 rpm/√K.

Full admission performance of the twin-entry turbine was also compared with measured performance on the same turbine with a single-entry housing. Fig. 3(a) shows the mass flow curves, while the efficiency characteristics are reported in Fig. 3(b) in terms of η'_t (defined as turbine isentropic efficiency η_t multiplied by turbocharger mechanical efficiency η_m). As expected in the case of radial turbines with a reaction degree of about 50 per cent, maximum efficiency η'_t occurs at u/c_s of approximately 0.70. Although the turbocharger compressor was used as a dynamometer, the experimental operating range resulted fairly large, as it should be in order to cover real on-engine operating conditions (Dale and Watson, 1986).

Mass flow rate was higher for the twin-entry casing due to a larger swallowing capacity (A/R respectively equal to 0.68 and 0.72), while a lower efficiency η'_t was found. This behavior may be explained by a wake effect (produced by the dividing tongue in every operating condition) that causes an axial maldistribution of the absolute velocity and of the flow angle at the rotor inlet (Yeo and Baines, 1990). Furthermore, the radial-to-axial turning in the rotor may cause a variation in the conditions at the rotor tip that can amplify this maldistribution. As a consequence, higher energy losses may arise from the mixing of the two different jets leaving each entry (Watson and Janota, 1982).

Constant speed characteristics were then evaluated in partial admission conditions, i.e., with zero flow in each sector alternatively. The two entries appeared to be significantly different both in terms of their mass flow rate and efficiency characteristics. Figs. 4(a) and (b) show turbine curves in full and partial admission for one of the tested non-dimensional speeds. Within the considered operating range, swallowing capacity and efficiency were always higher for entry 2 than for entry 1.

This dissimilar behavior in partial admission conditions, observed also by other authors (Pischinger and Wunsche,

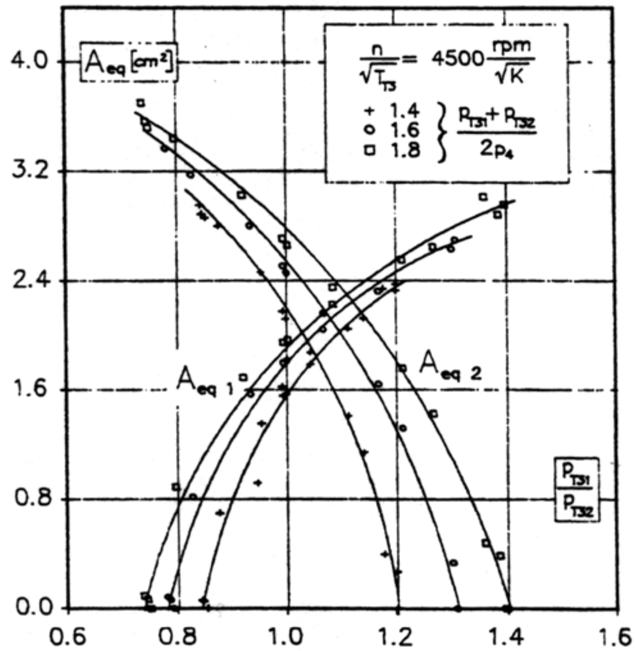

Fig. 5 - *Turbine mass flow curves with unequal admission (constant expansion ratio).*

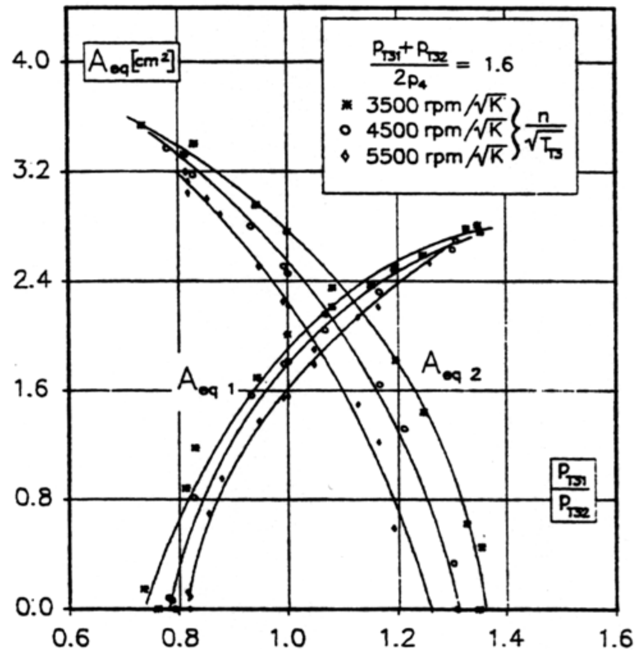

Fig. 6 - *Turbine mass flow curves with unequal admission (constant rotational speed).*

1977; Dale and Watson, 1986), can be discussed on the basis of the housing geometry of the tested turbine. The average value of the ratio between cross-sectional areas of the two entries A_1/A_2 was nearly 0.96, while the ratio between the volumes V_1/V_2 of the two portions of the divided scroll was approximatively 0.92. This may partly explain the apparent differences in swallowing capacity, which were not observed by other authors (Dale and Watson, 1986) on a symmetrical volute with identical cross-sectional areas and centroid radii. However, it can be seen (Fig. 4(a)) that the total mass flow in full admission cannot be evaluated by simply adding mass flow rate of each entry in partial admission.

As regards turbine efficiency η'_t, it may be affected by the flow distribution at the rotor inlet. It has been observed that partial admission is an extreme condition with reference to absolute velocity and flow angle at the rotor inlet (Yeo and Baines, 1990), which can give rise to windage losses and, therefore, to a lower turbine efficiency η'_t (Watson and Janota, 1982). In spite of this, comparing full and partial admission, no significant decrease in efficiency occurs at high turbine speed and high expansion ratio in the case of entry No. 2 (Pischinger and Wunsche, 1977), while lower efficiency values were measured for the inner entry (No. 1). However, differences between sectors cannot be further explained without careful measurements inside the turbine housing.

Unequal admission results

The knowledge of turbine characteristics with unequal admission can be very useful to achieve a better understanding of its on-engine behavior (i.e., in pulsating flow), since in pulse turbocharging the turbine instantaneously operates in these conditions.

Unequal admission measurements were developed at constant non-dimensional speed, ranging from zero flow to full flow in one branch and vice-versa in the other with different unequal conditions in-between. Therefore, turbine performance was defined from zero flow (partial admission) to full flow in each entry. Whereas it was possible to measure mass flow rate for each entry, only the total rotor power could be evaluated. As a consequence, only the turbine overall efficiency η'_t was calculated, and the behavior of each entry was not analyzed independently.

As regards mass flow rate, experimental results were represented in terms of equivalent isentropic flow area A_{eq} as a function of the inlet pressure ratio p_{T31}/p_{T32} of each sector and of the arithmetic mean expansion ratio $(p_{T31} + p_{T32})/2p_4$, following the work by Pischinger et al. (1977). Some results are reported in Figs. 5 and 6. The strong interaction between the two sectors is apparent. The equivalent flow area of each entry heavily depends on the pressure ratio p_{T31}/p_{T32}, and an increase of the flow area in one sector yields to a significant decrease in the other. Due to the housing and rotor asymmetry, equal mass flow

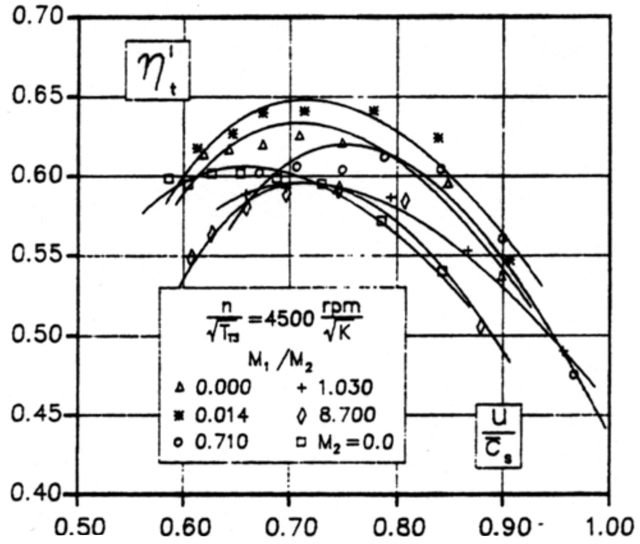

Fig. 7 - *Turbine overall efficiency curves in unequal flow conditions.*

rates are reached for a pressure ratio p_{T31}/p_{T32} higher than unity, increasing with mean expansion ratio and decreasing with non-dimensional speed. When the pressure ratio p_{T31}/p_{T32} is equal to 1.0, the swallowing capacity of each branch is not the same and the ratio between mass flows M_1/M_2 is approximately 0.710. Therefore, total mass flow in full admission cannot be evaluated as twice the corresponding value for one sector.

Turbine efficiency η'_t was calculated with reference to the sum of the isentropic power at each entry and represented against the mean blade-speed ratio $u/\bar{c}_s$, defined on the basis of a mass average of isentropic exit velocity $\bar{c}_s$ (Dale and Watson, 1986). As an example, experimental results at constant turbine non-dimensional speed are reported in Fig. 7. As it can also be seen in Fig. 4(b), the outer entry (No. 2) seems to have a greater impact in improving turbine efficiency. However, the highest efficiency occurs in unequal admission conditions with low, but not zero, mass flow through entry No. 1 (i.e., $M_1/M_2 = 0.014$). This effect may be explained by taking into account the higher windage losses that may arise in the rotor when there is no flow in one sector. A similar behavior was observed by Dale and Watson (1986), and may be related to alterations in the flow angle at the rotor inlet induced by the unequal and partial admission conditions (Yeo and Baines, 1990).

UNSTEADY FLOW RESULTS

In pulse turbocharging, unsteady flow from the engine is delivered to the turbine by two or more separate manifolds. In the case of a divided housing this leads to instantaneous partial and unequal admission of the turbine. The knowledge of pulsating turbine behavior in such operating conditions is therefore important to improve the engine-turbocharger matching.

Full and partial admission tests were developed in unsteady flow conditions. In addition the influence of a phase difference between pressure pulses at the two entries on pressure diagrams and average turbine performance was investigated.

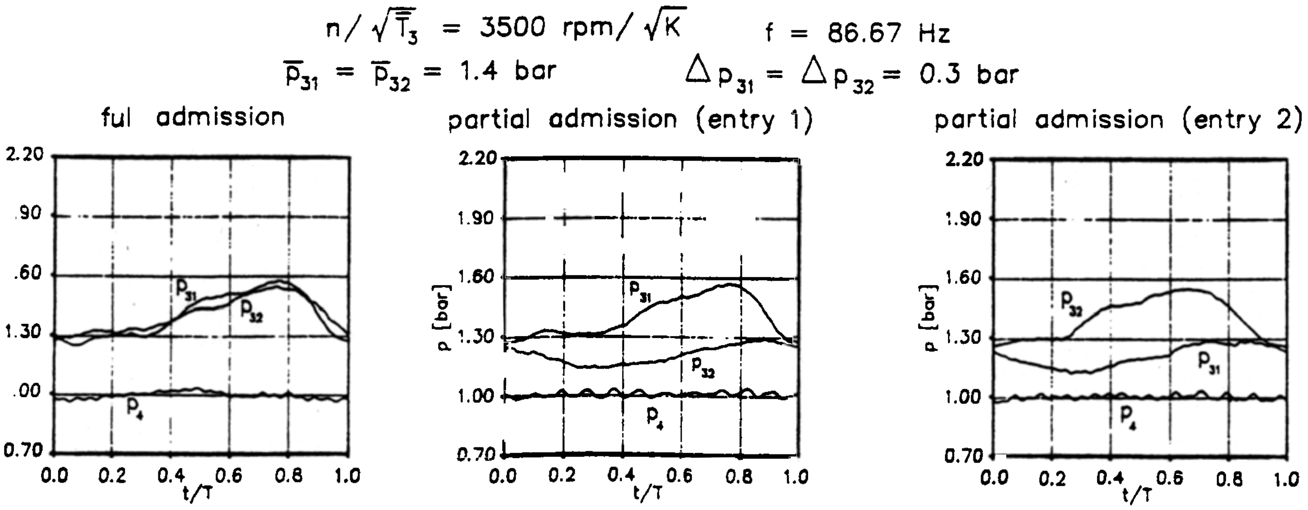

Fig. 8 *Full and partial admission inlet and outlet turbine pressure diagrams.*

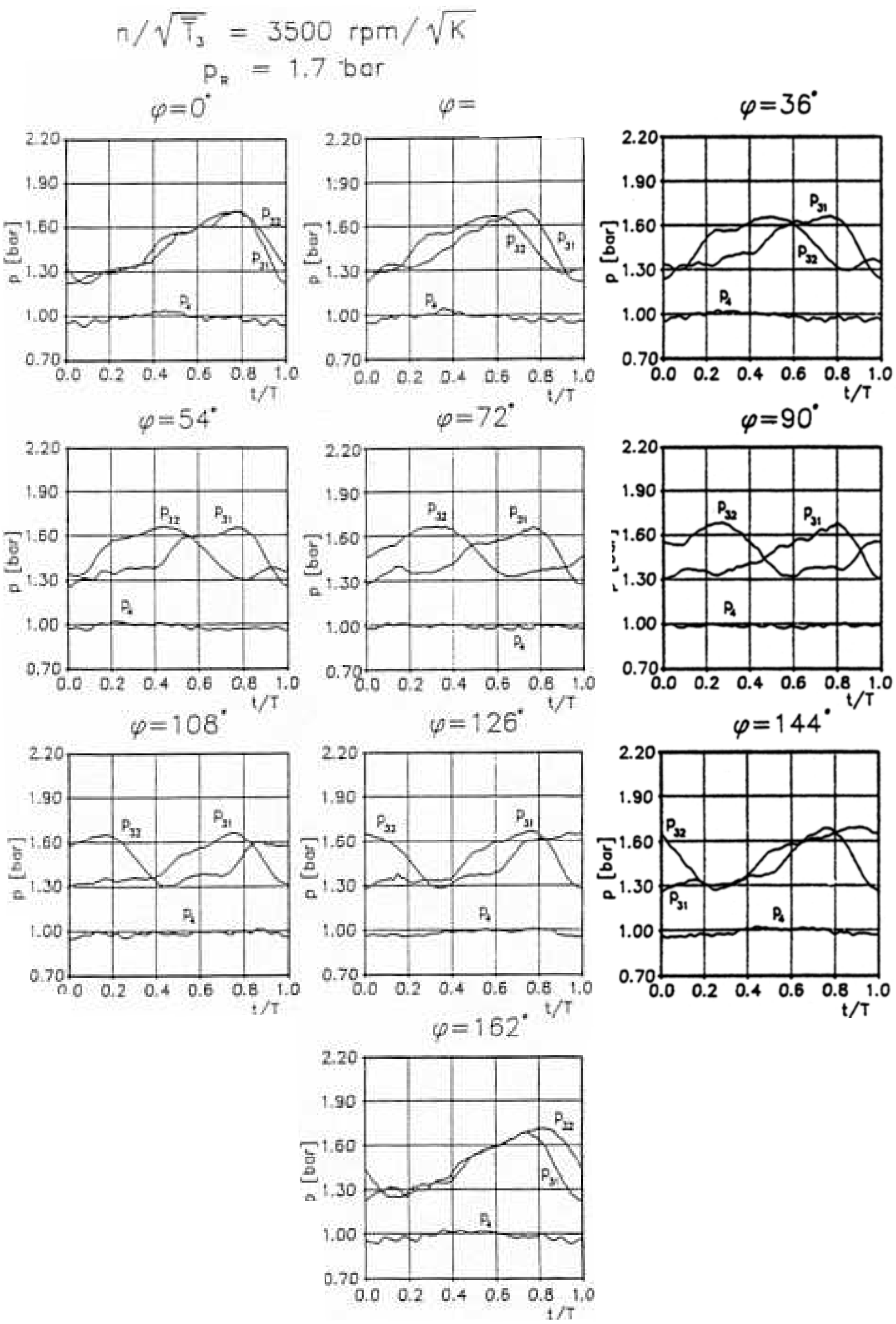

Fig. 9 - *Effect of pulse phase difference on inlet and outlet turbine pressure diagrams.*

Measurements were developed at a pulse frequency of 86.67 Hz; as in former stages of the study (Capobianco and Gambarotta, 1992), a constant turbine non-dimensional speed of 3500 rpm/√K was considered. Pulse amplitude and mean value at each turbine inlet were controlled through the pulse generator system of Fig. 1. Static pressures upstream ($p_{31}(t)$ and $p_{32}(t)$) and downstream ($p_4(t)$) of the turbine were recorded, while no attempt was made to evaluate instantaneous temperature levels due to the low response characteristics of the relevant transducers. Average turbine mass flow and rotational speed were also measured in pulsating flow operation, while mean turbine power was calculated on the basis of measurements on the turbocharger compressor.

In Fig. 8 typical full and partial admission pressure diagrams are compared referring to constant pulse amplitude and mean value at supplied turbine inlets. For each entry, no significant modifications of upstream pressure waveforms can be seen when mass flow is not zero. However, in partial admission operation, pulse amplitude was noticeable also for the not-supplied sector. Besides, a small delay of the corresponding wave with reference to the admitted entry can be observed. This may be explained on the basis of the propagation time of the leading pressure wave to the sector (and to the relevant measuring station) in which flow does not occur.

Pressure signals at the turbine exit generally have small amplitude. Slight oscillations at higher frequencies (approximately 1 - 2 kHz) are apparent both in full and partial admission (Fig. 8). They may be induced by wake flows downstream of the volute dividing tongue, related to local gas velocity and, therefore, to the turbine mass flow rate.

Partial admission average pulsating performance confirmed steady flow results. Mean turbine mass flow and torque proved to be always lower for the inner entry (No. 1), at the same mean inlet conditions. However, in pulsating flow operation, the ratio between the average swallowing capacity of the two sectors was generally closer to unity than in steady flow conditions (about 0.8 instead of 0.7). This may be an indication of a different flow pattern that could be confirmed only by measurements inside the turbine housing and rotor.

The effect of a pulse phase difference between the turbine entries was also analyzed. Tests were developed varying the phase difference angle (ϕ) between the pulse generator rotors in steps of 18°. Ten different conditions over the pulse period were then considered.

Fig. 9 shows a typical set of measured pressure signals upstream and downstream of the turbine for different phase angles. These diagrams are referred to constant pressure and temperature levels at the reservoir R (see Fig. 1) and to a fixed setting of the flow valves of the turbine feeding line.

Pulse shape at each turbine inlet proved to be slightly affected by pulse phase difference, as is apparent in Fig. 9. This suggests that interactions between the turbine sectors when varying the pulse phase are moderate. Moreover, a negligible effect on mean inlet pressure level of each entry and on averaged turbine mean expansion ratio was observed.

The influence of pulse phase differences on pressure oscillations amplitude is pointed out in Fig. 10, for the same operating conditions. It is apparent that both inlet and

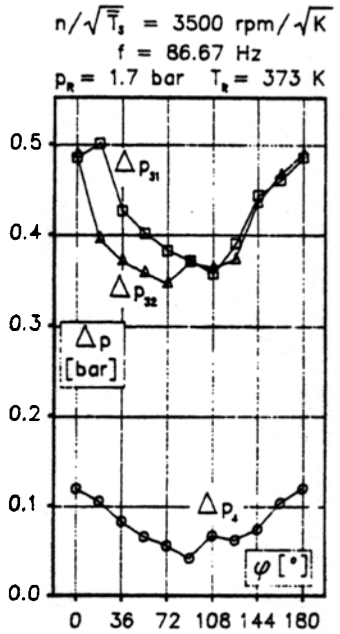

Fig. 10 - *Effect of pulse phase difference on pressure oscillations amplitude.*

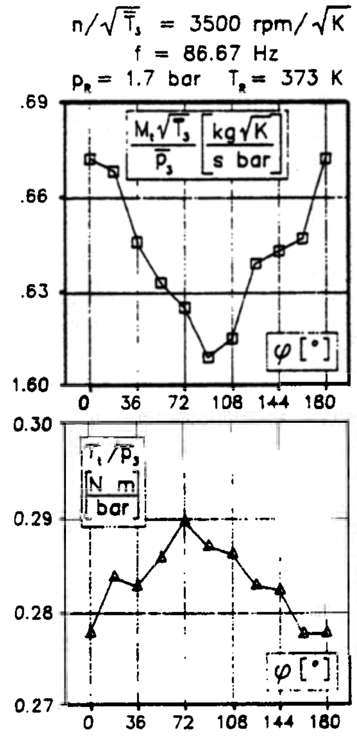

Fig. 11 - *Effect of pulse phase difference on mean pulsating turbine performance.*

outlet pulse amplitude reaches a minimum when pressure pulses are nearly equally spaced. A similar behavior was found for both entries.

Average mass flow rate and torque showed opposite responses when the pulse phase was varied (Fig. 11). Mass flow was lower for equally spaced pulses (and smaller pulse amplitudes), while torque increased to a maximum in the same conditions. The different influence of unsteady flow parameters on mass flow and torque is confirmed (Zinner, 1978; Capobianco and Gambarotta, 1992); however, further theoretical and experimental work seems necessary in order to explain completely this result.

CONCLUSIONS

The use of twin-entry radial nozzleless turbines is likely to remain a common practice in turbocharging vehicle diesel engines. In this case the turbine operates under unequal admission at each entry and in pulsating flow. Therefore, the knowledge of turbine behavior in such conditions is a basic requirement for the development of matching calculations to improve engine efficiency. However, very little research has been done on twin-entry turbines performance under these operating conditions.

The dedicated test facility which has been developed by the authors at DINE is now capable of testing different components and complete intake and exhaust systems of internal combustion engines in steady and pulsating flow conditions. With particular reference to turbochargers, it allows testing both single and two-entry turbines over a wide range of loads and speeds.

The results of an experimental investigation on the twin-entry turbine of a Garrett automotive turbocharger are presented and discussed in the paper. Steady and pulsating flow turbine performance was measured with reference to full, partial and unequal admission conditions. The influence of pulse phase differences was also investigated. Experimental results pointed out some peculiar behaviors:

(1) The twin-entry turbine efficiency is lower than that of a similar single-entry turbine. This effect has been observed by other authors and may be explained by the wake effect produced by the dividing tongue and the energy losses which arise from the mixing of the two flows leaving each entry.

(2) The two entries appeared to be significantly different both in terms of mass flow rate and efficiency characteristics. Full and partial admission tests showed that swallowing capacity and efficiency were always higher for entry 2 (outer entry from the center housing). This dissimilar behavior may be explained by taking into account the housing and rotor geometry, which shows an apparent asymmetry with reference to the meridional dividing plane.

(3) Total mass flow rate in full admission cannot be determined by simply adding mass flow rate of each entry in partial admission conditions. This result suggests that full and partial admission characteristics are not exhaustive in the definition of turbine behavior. As regards turbine efficiency, partial admission seems to be an extreme condition which can give rise to windage losses and therefore to a lower efficiency (except for the outer entry at high turbine speed and expansion ratio).

(4) A strong interaction between the entries and a lack of symmetry in their influence on turbine performance was highlighted both in partial and unequal admission conditions. The mass flow rate of each entry heavily depends on the pressure ratio p_{T31}/p_{T32}, and an increase of the mass flow in one sector results in a significant decrease in the other. Entry 2 seems to have a greater influence on turbine overall efficiency. Highest values were reached in unequal admission conditions with very low values of the ratio M_1/M_2 (approximately 0.014). This effect may be explained by supposing that windage losses in the rotor are the lowest when the mass flow through entry No. 1 is very low but not zero.

(5) In pulsating flow conditions, inlet pressure diagrams of supplied sectors were quite similar with full and partial admission. However, a significant pulse amplitude was measured also in the sectors where flow did not occur, with a little delay of this oscillation with respect to the leading one. Average partial admission turbine performance confirmed steady flow results as regards the differences in swallowing capacity and torque between the two entries.

(6) The effect of pulse phase differences was outlined through tests developed at constant operating conditions and fixed geometry of the turbine feeding line. Inlet pressure oscillations showed a similar shape and mean value when the phase difference between pulses was varied. However, amplitudes of pressure waves were lower in the case of equally spaced pressure pulses.

As regards average turbine performance, mass flow rate and torque showed an opposite behavior. Further work on this subject in order to fully explain experimental results is in progress at DINE.

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