Energy Conversion and Management 99 (2015) 72–80

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Steady and unsteady experimental analysis of a turbocharger for automotive applications

R. Bontempo, M. Cardone, M. Manna *, G. Vorraro

Dipartimento di Ingegneria Industriale, Università degli Studi di Napoli Federico II, Via Claudio 21, 80125 Naples, Italy

ARTICLE INFO

Article history:
Received 27 January 2015
Accepted 9 April 2015
Available online 24 April 2015

Keywords:
Turbocharger
Downsizing
Turbocharger test rig

ABSTRACT

The paper describes the steady and unsteady performance characteristics of a small size turbocharger typically employed in automotive downsized engine applications. The analysis is carried out by experimental means using an innovative hot gas generator system specifically designed for turbocharger testing which is capable of delivering a wide range of flow rates with adequate thermodynamic characteristics. More in detail, the gas generator consists of a medium size direct injection compression ignition Internal Combustion Engine (ICE) feeding the turbine of the test article. To independently set the hot gas mass flow rate and the turbine inlet temperature, the operating parameters of the aforementioned ICE are specified through an electronic control unit in a fully automated manner.

Compared to previously presented data [1] (Energy Procedia, vol. 45, pp 1116-1125, 2014), those reported herein have been collected with the help of newly installed equipment and controlling software allowing for the estimation of the thermal power transferred from the turbocharger to the environment. In particular, thanks to a first law analysis, the collected measurements have shown that the algebraic sum of the thermal power transferred to the lubricating oil as well as to the environment is roughly speaking 20–30% of the compressor total enthalpy change per unit time. Moreover, it has been shown that evaluating the compressor efficiency through classical expression based on the adiabatic assumption leads to a 5–10% relative error.

The improved experimental set up also allows for higher precision transient analysis both on the cold and hot side branch of the test article. While the steady-state performance maps of the turbocharger are readily obtained with the semi-automated testing procedure, the detailed analysis of the unsteady phenomena related for instance to the occurrence of mild and deep compressor surge events, are reproduced and thoroughly analysed using the rig in more advanced operating modes.

1. Introduction

In recent years, turbocharging internal combustion engines has become a very popular practice which is widely used to reduce the pollutant emissions and the fuel consumption especially for downsized propulsion system [2–8]. Specifically, different advantages can be achieved by coupling the downsizing and turbocharging techniques with no prejudice on the delivered power. In fact, the reduction of the engine displacement gives rise to a decrease of the weight, of the cost and of the mechanical friction losses. Moreover, at low loads, the throttle valve opening of a downsized spark ignition engine is generally bigger than the one of a conventional ICE delivering the same power, so that the associated pumping losses are reduced. Finally, the actual engine control systems are very often capable to avoid the typical drawback of supercharged engines, that is, a marked tendency to detonation. Recently, in order to investigate the most important phenomena occurring in turbochargers, several experimental facilities have been designed and manufactured. For example, the commercial test benches developed by the automotive research industries AVL [9] and FEV [10] both adopt a combustion chamber to feed the turbine, offering a compact and fully transportable solution for steady flow analysis. On the other hand many experimental facilities have also been proposed and employed to study more advanced problems, like the unsteady and unstable turbocharger flow regimes. The aforementioned test rigs are also frequently used to provide detailed experimental data for validation of numerical models. Luján et al. [11] described a turbochargers research test bench capable of reproducing compressor maps under pulsating or continuous flow conditions. Galindo et al. [12] defined the surge operating points by means of a special experimental setup in which the turbine is fed with a heavy duty diesel engine, while the centrifugal compressor is independently processing its own

* Corresponding author. Tel.: +39 081 7683287.
E-mail address: marcello.manna@unina.it (M. Manna).

http://dx.doi.org/10.1016/j.enconman.2015.04.025
0196-8904/

Nomenclature

h	static enthalpy
$\dot{m}$	mass flow
$\overline{\dot{m}}$	long time averaged mass flow
n	turbocharger revolutions per minute
p	static pressure
$\overline{p}$	long time averaged static pressure
$\dot{Q}$	thermal power
T	static temperature
$\dot{W}$	mechanical power
Greek symbols	
η_{is}	isentropic efficiency
$\eta_{presumed}$	presumed isentropic efficiency
Subscripts	
b	bearing
c	compressor
$corr$	corrected quantity
d	delivery
ext	used to indicate thermal powers transferred to the environment
h	housing
oil	oil
ref	reference quantity
s	suction
t	turbine
Superscripts	
0	stagnation quantity
Acronyms	
BSL	best straight line
CGG	cold gas generator
DCU	data acquisition and control unit
DS	deep surge
FS	full scale
HGG	hot gas generator
ICE	internal combustion engine
MS	mild surge
PID	proportional-integral-derivative control
rms	root mean square
rpm	revolutions per minute
TS	test section

mass flow rate. With the help of the same test rig, Serrano et al. [13] studied heat transfer phenomena in turbochargers which are of particular importance for the correct determination of the real compression work. Rajoo and Martinez-Botas [14] investigated a variable geometry mixed flow turbine with a purposely designed pivoting nozzle vane ring equipped with a heater to avoid the condensation of the water vapour during the expansion process within the turbine.

Another very research topic closely related to the analysis of turbochargers performance is the estimate of the heat transfer effects. Bohn et al. [15] performed a conjugate flow and heat transfer investigation of a turbocharger including the compressor, the oil cooled housing and the turbine. By means of a CFD based method, the authors analysed several case-studies characterised by different values of the mass flow rate and of the turbine inlet temperature. From this parametric study a one dimensional model has also been developed and it was clearly shown that the thermal energy transferred from the turbine to the compressor significantly influences the compressor performance. Chesse et al. [16] presented the results of the experimental tests carried out on a hot air supplied turbocharger test bench. The data show that the difference with the adiabatic conditions is considerable, especially at low compressor power. Romagnoli and Martinez-Botas [17] analysed the turbocharger behaviour operating under non-adiabatic conditions in order to assess the impact of the heat transfer phenomena on its performance. To this aim, a commercial turbocharger was directly installed on a 2.0 l diesel engine and the measurements were carried out for a range of engine speeds and loads. Finally, a one dimensional heat transfer model was also implemented and validated against experimental data. Other works dealing with the heat transfer effects are due to Aghaali and Ångström [18,19], Baines et al. [20], Bohn et al. [21,22], Casey and Fesich [23], Cormerais et al. [24], Hellström and Fuchs [25], Jung et al. [26], and Serrano et al. [27], but this list should not be regarded as exhaustive.

This paper deals with the analysis of the experimental results obtained through a turbocharger test bench in which a diesel engine is used as hot gas generator system. In comparison to a previously published work [1], many improvements in the rig layout and in the measuring chain are presented and discussed. In particular, three relevant aspects of the performance of a turbocharger can be more properly analysed through the actual configuration of the rig.

Firstly, both the compressor and the turbine stationary maps can be obtained in a semi-automated manner. Compared with those typically provided by the manufacturer, the performance maps obtained with the present facility are more extended both in terms of rpm and mass flow rate span. This means that in the compressor characteristic plane (pressure ratio versus mass flow), all desired *rpm* isolines can be obtained and that the mass flow rate is spanned in the whole operating range, i.e. from choke to surge limit. Likewise, on the turbine side, all *rpm* isolines can be also readily obtained, while the mass flow rate span is determined by the power range required to drive the compressor.

Secondly, thanks to a first law analysis of the whole turbocharger (see Section 4), the new experimental set-up also allows to estimate the heat transfer effects on the evaluation of the efficiency through the classical adiabatic assumption.

Thirdly and lastly, the unsteady phenomena related for instance to the occurrence of mild and deep compressor surge can also be thoroughly investigated.

In Section 2 the revised outline of the rig is briefly summarised, while in Section 3 the new measurement instrumentation is detailed. In Section 4 a first law thermodynamic analysis is carried out. This analysis, together with the collected experimental data, allows to quantify the discrepancy from the classical adiabatic assumption. Finally, in Section 5, the results related to the three aspects analysed in this paper (that is the construction of the steady state performance maps, the evaluation of the heat transfer effects and the analysis of mild and deep surge phenomena) are presented and discussed.

2. Experimental apparatus

As reported in Fig. 1, the experimental facility consists of the following four subsystems: a data acquisition and control unit (DCU), a test section (TS), a cold gas generator (CGG) and a hot