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Evaluation of heat transfer effects in small turbochargers by theoretical model and its experimental validation

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A R T I C L E I N F O

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A B S T R A C T

In the last few years, the effect of diabatic test conditions on compressor performance maps has been widely investigated leading some Authors to propose different correction models. The aim of the paper is to investigate the effect of heat transfer phenomena on the experimental definition of turbocharger maps, focusing on compressor performance. This work was developed within a collaboration between the Polytechnic School of the University of Genoa (Italy) and the testing center CRITT M2A (France). In particular, an original model for the correction of compressor steady flow maps is presented and discussed. The major benefit of this method is represented by the easiness of data post-processing, the data base economy, the reduced number of geometrical and physical input parameters required and the accuracy of the solution. Besides, this model does not need an out-of-standard test bench to obtain the compressor maps. In the paper, experimental tests under quasi-adiabatic conditions developed to validate the proposed model are reported. A satisfactory agreement between measured and calculated compressor maps is highlighted.

1. Introduction

Turbocharging plays today a prominent part in environmental impact reduction and energy demand of road vehicles, especially in conjunction with the downsizing concept and other technologies. Direct fuel injection [1], intercooling [2], fully flexible intake valves control [3,4] can substantially contribute to enhance automotive engines fuel economy. In Ref. [1] a synergic experimental and numerical approach is presented in order to individuate the optimal control strategy of a Gasoline Direct Injection (GDI) turbocharged engine with reference to a slightly lean burn combustion process. The adoption of an intercooler [2], interposed between the compressor outlet and the intake manifold, is the most important and the simplest method to increase the power, especially in the case of downsized engines. The adoption of a fully flexible valve actuation system allows reducing emissions and improving fuel economy both for diesel and spark ignition engines. In Ref. [3] the benefits of early inlet valve closure timings are compared to the benefits of cylinder disablement in a 4 cylinders common rail direct injection diesel engine. In Ref. [4] the advantage to use a Variable Valve Actuation system for a turbocharged downsized spark ignition engine is presented. In particular, the application of Miller cycle through late intake valve closure or early intake valve closure for knock mitigation at high load was experimentally investigated highlighting a fuel conversion efficiency improvement. As regards turbocharging technique, the availability of experimental turbocharger performance is an essential requirement, at least in steady flow conditions, in order to optimize turbocharger-engine matching calculation.

Turbine and compressor maps generally available are measured under steady flow condition and at different operating temperature for compressor and turbine, with or without water-cooling circuit. This aspect strongly affects the heat flux from the hot turbine side towards the lubricating oil and the compressor (through the intermediate casing). Therefore, the working temperature adopted during tests heavily influences turbocharger experimental maps, mainly in terms of efficiency. Some Authors analysed this aspect in hot and cold experimental condition [5], approaching this problem under both theoretical and experimental studies in engine test bench [6,7]. In Ref. [6] an experimental evaluation of the impact of heat transfer on a turbocharged diesel engine under non-adiabatic conditions is shown and a 1D heat transfer model is also presented by means of lump capacitances. In Ref. [7] turbocharger heat transfer losses are modelled using a lumped capacitance model

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Nomenclature

Definitions

n_{cr}	compressor corrected rotational speed
M_{cr}	compressor corrected mass flow rate
β_{cTT}	total-to-total pressure ratio
η_{cTT}	total-to-total efficiency

Notation

a	speed of sound
A	area
c	absolute velocity
C	torque
D	diameter
h	enthalpy per unit mass
K	heat conduction constant
k_{df}	disk friction parameter
k'_c	heat transfer parameter
M	mass flow rate
Mu	tip speed mach number
n	rotational speed
p	pressure
q	specific heat flow per unit mass flow
$\dot{Q}$	specific rate of heat exchange
R	radius
T	temperature
u	rotor tip speed
U	conductance
w	relative velocity
z	compressor blade number

Greeks

α	velocity absolute angle
β	relative flow angle
η	efficiency
ρ	density
Δ	variation
φ	flow coefficient
Ψ	work coefficient
ω	angular speed

Subscripts

ad	adiabatic
ap	apparent
b	blade
c	referred to compressor
df	referred to disk friction
dia	diabatic condition
eul	eulerian
in	referred to the inlet
is	isentropic condition
m	meridional component
max	maximum value
mean	mean value
oil	referred to lubricant
q	referred to heat exchange
real	real condition
R	ratio
s	slip component
sh	shaft
S	static condition
tc	turbocharger
T	total condition
u	tangential component
WC	water-cooling
0	reference condition
1	referred to compressor inlet
2	referred to compressor outlet
2d	referred to compressor diffuser exit
2i	referred to compressor impeller exit
2v	referred to compressor volute exit
3	referred to turbine inlet

coupled to a 1D whole-engine simulation software, focusing the study on the influence of turbocharger outlet temperatures and predicting the engine performance.

This paper begins from a preliminary study [8] based on the analysis and the modification of three models for heat transfer correction map available in the open literature [9–11] selected for easiness in terms of experimental database or input data requirement. The model proposed by Sirakov and Casey [9] requires as input data a single compressor map, without further experimental information related to different thermal boundary conditions. The model proposed by Grigoriadis et al. [10] assumes that the heat exchange between the compressor and the other components of the turbocharger is mainly driven by temperature differences and compressor mass flow rate. The last selected model proposed by Walther et al. [11] is based on the assumption that the impact of heat transfer phenomena on compressor efficiency is reduced at higher level of compressor mass flow rate in the case of constant boundary thermal conditions. Starting from the achieved preliminary results, a model jointly developed by the University of Genoa (Italy) and the testing center CRITT M2A (France) is presented and critically analysed in the paper. The aim of the model is to correct turbocharger compressor steady flow map, removing the heat transfer effect. In order to validate this approach, an extensive experimental study was developed on a typical state-of-the-art automotive turbocharger compressor installed at the test rigs operating at the University of Genoa (UNIGE) and at CRITT M2A. The experimental study was performed focusing on the definition of compressor steady flow performance maps measured at different turbine inlet temperatures, oil and coolant temperature levels and compressor inlet pressures. A quasi-adiabatic map was also measured as a reference for the validation of correction model results. This last was achieved maintaining the average oil temperature equal to compressor outlet temperature and turbine inlet temperature in order to minimize the heat fluxes between the components.

A satisfactory result was attained through the adoption of the correction model here proposed, as shown by corrected map which close-fits the quasi-adiabatic curves. Besides, this procedure does not require a lot of unusual information, not strongly affecting the automated experimental sequences even needing more investigation time demand. The proposed correction model could represent a preprocessing tool of compressor maps generally available, thus improving the engine-turbocharger matching calculations. Furthermore, it is important to remark that corrected compressor maps allow estimating a more reliable turbine thermo-mechanical efficiency, generally assessed on the basis of compressor power absorption.