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Turbocharger heat transfer and mechanical losses influence in predicting engines performance by using one-dimensional simulation codes

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ABSTRACT

The exhaust energy can represent up to 40% of the fuel chemical energy in turbocharged internal combustion engines. In order to calculate properly the available energy of the exhaust gases, a critical parameter is the temperature downstream the turbine. The prediction of this temperature will also benefit the two-stage turbochargers and after-treatment modelling that affects brake specific fuel consumption, exhaust gases emissions and the scavenging process.

In this paper, turbocharger heat transfer losses have been modelled using a lumped capacitance model coupled with one-dimensional whole-engine simulation software. The data from the simulations of a turbocharged Diesel engine, with and without the turbocharger heat transfer model, have been compared with experimental measurements performed in an engine test bench. The analysis is focused on studying the influence in turbocharger outlet temperatures and predicting the engine performance. The main result of the study is the improvement in the prediction of both compressor and turbine outlet temperatures (up to an improvement of 70 K). The results from the model allow analysing how heat transfer losses are split in the turbocharger and quantifying the importance of heat transfer phenomena in turbocharger efficiency, at full load conditions and as a function of engine speed.

1. Introduction

The research on internal combustion engines is currently focused on energy optimisation and the reduction of fuel consumption and pollutant emissions. Different strategies to fulfil these objectives have been studied. Engine downsizing combined with a high level of turbocharging is one of these strategies [1]. Moreover, turbocharging affects other engine systems such as EGR (exhaust gas recirculation) [2], cooling and combustion; all of them related both with engine BSFC (brake specific fuel consumption) and engine emissions. In addition, the phenomena taking place internally to the turbocharger affect engine performance [3]. Turbocharger heat transfer is one of these phenomena. In order to estimate the heat fluxes in a turbocharger, working coupled to the engine, several approximations proposed by different authors can be employed, as described below.

Some authors have studied the phenomena experimentally, both in a gas stand [4] and in an engine test bench [5], while other studies are theoretical [6]. The gas stand tests aim to decouple the turbocharger phenomena from the ones associated to the engine. The engine test bench experiments represent the closest approximation to real vehicle operation conditions. An important effort has been made by some authors [7] in analysing different heat transfer conditions in the turbocharger on engine operation. These studies conclude that the importance of heat transfer phenomena in the overall power exchange inside the turbocharger can be significant at low and medium turbocharger speeds.

Other authors [8] have performed CFD (Computational Fluid Dynamics) studies in order to better understand the phenomena and their implications. These studies show the relevant heat transfer paths and their magnitude. However, due to computational limitations, this approach cannot be used if a whole engine has to be modelled.

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Nomenclature

a	sensor uncertainty
c_p	specific heat capacity J kg^{-1} K^{-1}
h	specific enthalpy J kg^{-1}
K	turbocharger speed constant rpm/W
p	pressure Pa
s	specific entropy J kg^{-1} K^{-1}
n	number of measurements
N	turbocharger speed rpm
T	temperature K
$\dot{m}$	mass flow kg s^{-1}
$\dot{Q}$	heat flow W
u	standard deviation
$\dot{W}$	mechanical power W
$\dot{W}'$	mechanical and heat power W

Greek symbols

η	efficiency
Δ	increment or drop

Subscripts and superscripts

0	total conditions
1	compressor inlet
2	compressor outlet
3	turbine inlet
4	turbine outlet
a, *adiab.*	adiabatic conditions
c	refers to compressor
C	compressor node
diab.	diabatic conditions
GAS	gas node
t	refers to turbine
T	turbine node
*H*1	turbine housing node
*H*2	central housing node
*H*3	compressor housing node
W	water node
IC	compressor inlet
OC	compressor outlet
OC_s	isentropic compressor outlet
IT_1	adiabatic turbine inlet
OT	turbine outlet
OT_s	isentropic turbine outlet
S	isentropic
TG	refers to turbocharger
mech	refers to mechanical losses

Abbreviations

AC	alternating current
BSFC	brake specific fuel consumption
CALMEC™	combustion diagnosis tool
CFD	computational fluid dynamics
COT	compressor outlet temperature
ECU	engine control unit
EGR	exhaust gas recirculation
ETE	effective turbine efficiency
EVO	exhaust valve opening
HT&ML	heat transfer and mechanical losses model
ORC	organic Rankine cycle
TOT	turbine outlet temperature
VGT	variable geometry turbine

The experimental approach is closer to the real application but it is inefficient in engine design because a test campaign of prohibitive economical cost would be needed. The CFD approach is able to save part of these costs but at high temporal costs and it cannot be used in a whole engine model (the computational cost would be prohibitive). Between both options, a 1D modelling codes such as GT-Suite can be used, which are extensively used by engine manufacturers in design and research. This approach makes possible the prediction of variables related to both the engine and the turbocharger, crucial when overall conclusions are needed. Some authors have used this methodology in predicting different variables related to the engine and turbocharger system comparing with experimental results, and considering different approaches for the turbocharger [9].

The present work tries to clarify the strong debate about the influence of turbocharger heat transfer and mechanical losses (HT&ML, from now on) models on engine performance prediction. Some authors have performed experimental measurements in gas stand concluding that the effect of turbocharger heat transfer is irrelevant compared to turbocharger mechanical power at high engine loads [10]. However, more recent studies [11] show that heat transfer in the turbine always represent an important part of its enthalpy change, being more relevant in the low torque region. Some authors [12] have measured turbocharger performance in an engine test bench concluding that at high engine speeds and loads the deviation between adiabatic and non-adiabatic compressor efficiency is small. Nevertheless, other authors [13] have pointed that at higher powers the distribution of heat transfer during compression process has important effects. It is widely accepted that the influence of HT&ML models is important at part loads and at transient operation [14]. However, neither studies quantifying the influence of these models on engine parameters nor studies indicating the engine parameters affected are found in the literature. In the present work the importance of these models on full load simulations is shown.

In order to clarify this controversy, a simple lumped model able to predict heat transfer and mechanical losses phenomena in turbochargers is used, coupled with a complete engine model built in GT-Power. Engine full load conditions at different speeds have been simulated and compared with experimental results. Experimental tasks have been described in the first place; focusing on the description of test rig and equipment used; the different turbochargers and engines that have been tested; the description of the testing methodology and the results of the tests. The second part of the paper is focused on the modelling work, starting with a brief description of the HT&ML model used, followed by a description of the engine model in GT-Power, and finishing with a description of the performed simulations. Then, a discussion of the obtained results with the different models and their comparison with experimental data is presented. Finally, the main conclusions of the work are summarised.

2. Experimental work

The experimental tasks of this work have been performed in an engine test bench using two different turbochargers (with and without water cooling) coupled to a 2 L engine, but emulating 1.6 L engine for the non water-cooled turbocharger (downspeeding).