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An experimental investigation of internal heat transfer in an automotive turbocharger compressor

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HIGHLIGHTS

- The heat transfer internal to a turbocharger compressor was experimentally investigated.
- Internal heat transfer was deduced from surface temperature measurements by an infrared camera.
- A correction approach of the measured diabatic efficiency has been proposed.
- The proposed approach was validated by quasi-adiabatic compressor performance measurements.
- Corrected maps can improve commercial codes for engine-turbocharger matching calculation.

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ABSTRACT

An experimental investigation developed on a small turbocharger compressor for automotive application is presented. The study focuses on the effects of internal heat transfer on compressor efficiency, evaluated for different values of inlet pressure, mass flow rate and compressor rotational speed. Infrared thermography has been used to evaluate the heat transfer rate from the turbine to the compressor and to correct the measured compressor diabatic efficiency. The approach has been validated by performing additional measurements under quasi-adiabatic conditions, avoiding map distortion due to heat transfer. Simple relationships for the prediction of internal heat transfer, validated against the measured values, have been proposed. The practical significance of the results, with reference to turbocharger compressor performance, is outlined.

1. Introduction

Turbocharging technology is today an important key to solve environmental problems in the Automotive Industry, with special reference to the reduction of exhaust emissions and fuel consumption [1,2]. It is well known that this goal is achievable for Spark Ignition engine applications if charge boosting is associated with other technologies such as downsizing concepts, fully flexible valve trains and direct injection [3,4].

The miniaturisation of engines such as micro gas turbines and turbochargers poses significant challenges in heat management due to the close proximity of the hot and cold components [5]. In turbocharger (TC) units, the improvement of TC-engine matching calculation can be reached if the performance of turbine and compressor is accurately measured and associated heat transfer processes are correctly accounted for. The thermodynamic analysis of compressor and turbine in turbochargers is based on the comparison of the isoentropic adiabatic process and the diabatic non-ideal process. The latter represents the actual process that occurs in turbochargers during engine operation. An adiabatic non-ideal process can be reproduced in a laboratory test if precautions are taken to minimize internal and external heat transfer. In an adiabatic non-ideal test, the change in total enthalpy across the machine, which can be measured by means of inlet and outlet total temperature, is equal to the shaft power. In a diabatic process or test, the change in total enthalpy across the machine is equal to the algebraic sum of work and heat transfer rates.

The practical purpose of an adiabatic test program is to obtain an accurate measurement of the work transfer, and of the real efficiency of compressor and turbine (unaffected by internal and external heat transfer rates). In fact, the heat flow leads to an apparent increase of the power absorption and an apparent drop in efficiency of the compressor. However, lack of understanding

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Nomenclature

Definitions

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

Notations

A	cross-sectional area
C	conductance
h	enthalpy per unit mass
k	thermal conductivity
M	mass flow rate
n	rotational speed
p	pressure
Q	heat transfer rate
T	temperature
x,y	Cartesian coordinates

Greeks

Δ	variation
η	efficiency

Subscripts

A,B	coefficients in Eqs. (8) and (9)
bh	bearing housing
c	compressor
dia	diabatic condition
int	internal
is	isentropic condition
$mean$	mean value
oil	lubricant
$real$	real condition
T	total condition
w	wall
0	reference condition
1	compressor inlet
2	compressor outlet
3	turbine inlet

of the heat transfer effects as well as the high costs associated with testing facilities often discourages efforts on this topic and manufacturer maps frequently consider the compression and expansion process within turbochargers to be adiabatic.

A number of literature studies focus on the effect of heat transfer on compressor performance, suggesting a modelling approach to correct measured efficiency maps [6–20]. Bohn et al. [6,7] describe a computational and experimental analysis of the internal heat transfer in turbochargers. A 3D calculation was developed for the compressor, the bearing housing and the turbine taking into account boundary conditions derived from experimental data. An infrared thermal camera and resistance thermometers were adopted to measure temperature surfaces. The Authors proposed a heat transfer correlation based on inlet temperature of both compressor and turbine, on compressor mass flow and on geometrical and material characteristics of the turbocharger. Casey and Fesich [8] examined different compressor efficiency definitions for diabatic flows showing that the classical isentropic efficiency has severe deficiencies (or is completely flawed) when dealing with diabatic flows. The Authors demonstrated the advantages of the polytropic efficiency for a diabatic process in a compressor, as it considers the changes between the actual end states of the real compression path. The polytropic analysis provided a simple way of taking into account heat transfer during the compression process in addition to the usual polytropic efficiency. Baines et al. [9] and Romagnoli and Martinez-Botas [10] proposed 1D heat transfer network models based on the well known correlations available for heat conduction, radiation and convection. Calculations have been validated by comparing calculated and measured exit compressor temperatures. Chesse et al. [11] experimentally showed that the effect of internal heat transfer is insignificant if compared to turbocharger mechanical power at high engine loads. The experimental activity was developed in adiabatic conditions adjusting the average turbine temperature to the average compressor temperature. Besides, the turbocharger was thermally insulated to minimize internal and external heat transfer. Sidorow et al. [12] presented two different modeling approaches, considering both heat outflow from the turbine and heat inflow into the compressor, and are validated against measurements performed in a dynamic engine test bench. Both proposed models seem to be applicable for onboard fault diagnosis. Sirakov and Casey [13] proposed a model for the correction of the efficiency map based on the simplified assumption that a single heat transfer coefficient could apply to all operating conditions and compressors tested. Olmeda et al. [14] developed a methodology to calculate heat fluxes inside a turbocharger for diesel passenger car application. The heat transfer phenomenon was analyzed by using a one dimensional lumped model, which takes into account the heat fluxes between different turbocharger elements as well as the heat fluxes between the working fluids and turbocharger elements. The whole turbocharger has been split into different metal nodes, in order to separate aerodynamics from heat transfer effects and to permit the study of compressor and turbine behaviour in a separated way. Grigoriadis et al. [15] assumed 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. Payri et al. [16] presented a model for the evaluation of external heat transfer that takes into account radiation and convective phenomena. The model considers a simplified geometry of the whole turbocharger, requiring easily obtainable geometric data (detailed turbocharger geometry is not necessary). The proposed procedure has been validated against experimental measurements performed on an engine test bench, using wall thermocouples installed on the turbocharger. According to the Authors' opinion, the most important external heat flux comes from turbine external surface, while external heat fluxes from the bearing housing are negligible and external heat flow associated with the compressor external surface can be reversed, i.e., it can be lost or absorbed depending on the running conditions. Serrano et al. [17] investigated turbocharger heat transfer losses by using a lumped capacitance model coupled with a 1D whole-engine simulation software. The main result of this study was the improvement in the prediction of both compressor and turbine outlet temperatures. In a different paper, Serrano et al. [18] provided correlations for the convective heat transfer coefficient by measuring heat fluxes between different turbocharger elements. Experimental tests were developed in "almost-adiabatic" conditions to minimize heat transfer, and in hot conditions. A model for the correction of