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Research Paper

Centrifugal compressor influence on condensation due to Long Route-Exhaust Gas Recirculation mixing

J. Galindo, R. Navarro, D. Tarí*, G. García-Olivas

CMT – Motores Térmicos, Universitat Politècnica de València, Camino de Vera, 46022 Valencia, Spain

HIGHLIGHTS

- Simulations of LR-EGR T-joint and centrifugal compressor to predict condensates.
- Operating conditions and geometry greatly influences condensation production.
- Impact of the compressor on the condensation production results negligible.
- The possibility of safely removing the compressor reduces computational effort.

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ABSTRACT

State of the art techniques for reducing pollutant emission in internal combustion engines often require local flow assessment, specially in the air management field. This work addresses the interaction between a turbocharger compressor and the 3-way long-route EGR joint, where exhaust gases of the combustion are mixed with fresh air. A validated methodology for compressor simulation is combined with a validated condensation model for this work. Numerical simulations of two different working points with three flap positions are conducted. The influence of these operating conditions on the flow field is evaluated. Particularly, there is a connection between the mixing of both steams and the generation of water condensates, responsible for the erosion of the impeller and the loss of compressor efficiency. Moreover, neglecting the impact of the compressor presence on the condensation production is shown to be of low magnitude, so that simulations without the compressor are regarded as accurate, thus reducing the computational effort by two orders of magnitude.

1. Introduction

With more and more evidences of the pollutant emissions being partially responsible for the climatic change and health issues, the regulations have been progressively tightened during the latest years, particularly for Internal Combustion Engines (ICE). One of the most developed emission control technique used in ICE to achieve the required emission reduction is the Exhaust Gas Recirculation (EGR) [1–3]. This process consists in reintroducing back in the cylinders a fraction of the exhaust gases resulted from the combustion process mixed with fresh air. Due to this mixing, the maximum temperature is lowered during the combustion, drastically reducing the formation of nitrogen oxides [1].

Moreover, due to the common usage of turbochargers in ICE, two recirculation paths are possible. The most common configuration is called Short Route-EGR (SR-EGR), in which the intake and exhaust manifolds are directly connected, i.e., the gases are drained upstream the turbine and reintroduced downstream the compressor. Alternatively, the Long Route-EGR (LR-EGR) configuration consists in extracting the exhaust gases downstream the turbine and after-treatment elements and reintroducing them right upstream the compressor. In both cases, a cooler to reduce the temperature of the gases and valves to control the mass flow rate are usually mounted in the EGR line.

On the one hand, using the SR-EGR option reduces the pumping losses [1] and increases the turbocharger durability, since only dry air is passing through the compressor. However, the operation of the compressor is moved towards the surge limit and the distribution of exhaust gases through the different cylinders is not homogeneous [4,5]. On the other hand, the LR-EGR alternative takes the gases downstream of the after-treatment elements, avoiding issues caused by the accumulation of pollutant and acidic deposition in the EGR line, the intake manifold or the inlet ports. The main problem of the LR-EGR technique is the

* Corresponding author.
E-mail addresses: galindo@mot.upv.es (J. Galindo), ronagar1@mot.upv.es (R. Navarro), datade@mot.upv.es (D. Tarí), guigarol@mot.upv.es (G. García-Olivas).

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Nomenclature

List of symbols

c_p	isobaric specific heat capacity, J·kg^{-1}·K^{-1}
L	latent heat, J·kg^{-1}
N	compressor speed, rpm
$\dot{m}$	mass flow rate, g·h^{-1}
p	pressure, Pa
S	source term
T	temperature, K
$\vec{v}$	velocity, m·s^{-1}
w	specific humidity, g$_{H_2O}$·kg$^{-1}_{air}$
Y	mass fraction
Δt	characteristic time, s
ϵ	error, %
ρ	density, kg·m^{-3}

Sub- and superscripts

abs	absolute
air	dry air
comp	complete
ener.	energy
mom.	momentum
liq	liquid water
red	reduced
rel	relative
vap	vapor component

List of abbreviations and acronyms

3D	three dimensional
CFD	computational fluid dynamics
DES	detached eddy simulation
EGR	exhaust gas recirculation
ICE	internal combustion engines
LIC	line integral convolution
LR-EGR	long-route EGR
Op	operating
SR-EGR	short-route EGR

condensation of the water vapor of the exhaust gas when its temperature is lowered below the dew point. This may occur in the EGR cooler or in the T-joint upstream the compressor, when the exhaust gases are reintroduced to the intake duct and are mixed with fresh (and potentially cold) air. Condensation in the cooler is usually found during the warming up whereas condensation in the T-joint is strongly noticeable with ambient temperatures below 10 °C [6]. Appearance of liquid water upstream the compressor is critical if droplets reach the impeller. The impact velocity of the droplets against the impeller is high enough to produce erosion on the leading edges, reducing the compressor efficiency and posing a risk to the turbocharger integrity if produced continuously, as seen by Karstadt et al. [7].

Due to the relevance of this issue, it is interesting to analyze the condensation phenomenon in order to find potential solutions. Condensation depends on the flow distribution and turbulence, i.e., how the streams mix. So, a thorough analysis should be addressed using a 3D-CFD approach. Previously, different authors have dealt with similar stream mixing problems [8–10], condensation modeling [11,12] or both phenomena [13]. 3D-CFD has shown to be also a good tool for researchers to analyze the flow field of centrifugal compressors [14,15]. In the particular case of condensation produced in a LR-EGR T-joint, the compressor presence as an active element on the process may be of importance. Unfortunately, modeling the whole compressor along with the LR-EGR T-joint with accuracy implies a computational effort remarkably larger than simulating only the T-joint, as will be shown in Section 4.4.

This work is devoted to assess the influence of the operating conditions and the intake counter-pressure flap angle of a LR-EGR T-joint in the mixing process and generation of condensates, which is responsible for worsening the compressor efficiency by producing erosion on the leading edges of the compressor. Due to the difficulty of performing local measurements without being too intrusive, CFD simulations are carried out using the commercial code STAR-CCM+ [16]. The numerical setup is obtained from an experimentally validated previous work and the condensation model used was also validated with experimental data. The impact on computational effort of considering the compressor will be addressed as well.

In Section 2 the mesh and simulation setups will be detailed and the condensation model summarized. Then, the methodology, including the operating points and specific geometrical configurations, will be explained in Section 3. The results and the discussion are written in Section 4 and finally, the concluding remarks are highlighted in Section 5.

2. Numerical configuration

2.1. Geometries and mesh

As aforementioned, there are two main regions of interest in the current study; the LR-EGR junction and the compressor, which together form the complete geometry, as shown in Fig. 1. The particular LR-EGR junction selected for this work is a T-joint, as can be seen in Fig. 2. It has two perpendicular inlets, one for the intake of fresh cold air (left branch) and one for the warm and humid EGR (bottom branch), with a counter-pressure flap on each duct for controlling the ratio of mass flow rates (known as EGR rate). The length of the intake pipes, from each flap to their inlet boundary is three corresponding diameters [17]. The T-joint discharges into the compressor wheel (right branch of Fig. 2). Fig. 3 shows that the complete geometry of the compressor is considered, i.e., 360°-resolved wheel, diffuser, volute and outlet duct, which is 5 diameters long [18]. There will be two sets of simulations: complete domain (T-joint with compressor; Fig. 1) and reduced domain (T-joint alone; Fig. 2). For the latter, the section at the end of the cone is extruded one and a half diameters, thus reducing the impact of the

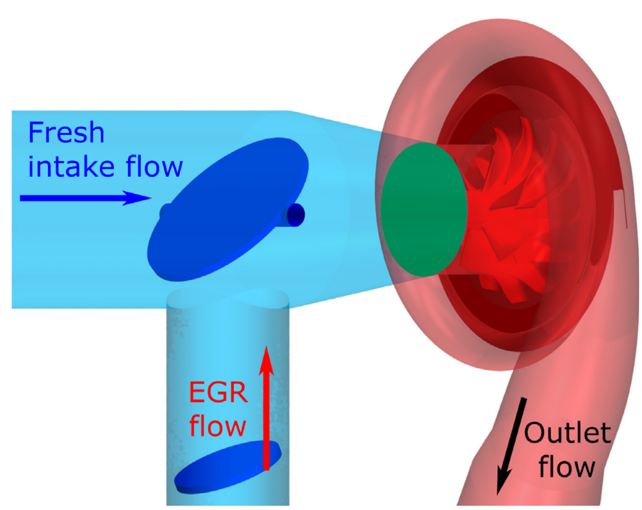

Fig. 1. Geometry included in the complete domain.