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Flow and thermal management of engine intake air for fuel and emissions saving

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A B S T R A C T

Charge air cooling is the typical technique to reduce temperature of the engine intake air, increasing air density and improving cylinder filling and engine volumetric efficiency in present turbocharged diesel engines. Usually, charge air is cooled by environmental air that crosses a heat exchanger placed in front of the vehicle: its cooling capacity is related to the vehicle speed and other constraints (presence of the main radiator). This leads to an intake air temperature from 30 to 80 °C, depending on engine load, external air conditions and vehicle speed again. If the intake air was more cooled down, the engine volumetric efficiency would be further increased. This can only be done by the use of a dedicated cooling fluid, operating at lower temperature with respect to external air. In this paper, therefore, an evaporator, mounted in parallel with the one of the refrigeration unit used for cabin cooling, was placed on the intake line of a turbocharged diesel engine (F1C IVECO engine), tested on a high speed dynamometer bench: the air refrigeration unit is also composed by a compressor, a condenser and a thermostatic expansion valve. The effects of the undercooling of the charge air have been experimental assessed in terms of fuel consumption and regulated emission reduction, evaluated on the most common engine operating points. Mechanical power demand of the compressor has obviously taken into account in order to assess overall benefits. Achieved net fuel consumption is in the order of 1% at fixed conditions operating the engine as a light duty type, when the intake air sub-cooling is turned on. A benefit on the regulated emissions has been observed (Nitrogen Oxides, Soot) regardless of the setup of the engine combustion processes (injection time, fuel distribution for each injection, Exhaust Gas Recirculated rate). Unburned hydrocarbon and Carbon monoxide behavior, on the other hand, deserves some more attention and call for the re-calibration of the previously cited combustion control parameters.

1. Introduction

Several international agreements and commitments have been recently done, aimed to the reduction of the carbon dioxide (CO_2) emissions in the environment. In particular, in the transportation sector, European Community proposed an emission limit of 67 gCO_2/km for passenger cars and light duty vehicles by 2030 and it has been followed by most of the other governments. In addition, very stringent regulation (EURO6) is still present on the primary pollutants (Nitrogen Oxides - NOx, carbon monoxide - CO, unburned hydrocarbon – HC - and particulate matter - Soot) and the research for innovative technologies that are able to satisfy these limits is very urgent.

In this framework, engine downsizing is one of the most explored opportunities, which is conventionally achieved through a reduction of the number of cylinders and, so, of the total displacement of the engine [1]. The challenge is to employ technologies to increase specific output avoiding drawbacks on other expected engine and vehicles performance (torque, power, acceleration, fun to drive, etc.) [2]. At present, a very common and proven way to improve cylinder filling and engine power is supercharging [3], which demonstrated benefits. A proper approach in terms of calibration, however, should be defined to make effective this technique [4].

Supercharging is based on a compressor (mechanically driven or coupled to an exhaust gas turbine - turbocharger) which increases intake air pressure. This compression stage heats up the charge and, so, it needs to be cooled before entering in the cylinders: a colder air, in fact, has higher density and produces a better cylinder filling, improving volumetric efficiency and increasing brake specific torque. The effect of the higher density intake air has been widely exploited in the literature, showing benefits in terms of performances and emissions regardless of fuel type: higher thermal efficiency has been demonstrated with lower intake air temperature in diesel/methanol duel fuel engine, as well as

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Nomenclature

a	Wiebe exponent
A/C	air conditioning
b	Wiebe coefficient
BMEP	brake mean effective pressure
BSFC	brake specific fuel consumption
C	torque, compressor
CAC	charge air cooler
CAT	catalyst
COP	Coefficient of Performance of A/C unit
DPF	diesel particulate filter
ECU	electronic control unit
EGR	Exhaust gas recirculation
FMEP	friction mean effective pressure
HFM	hot flow meter
IAC	intake air cooling
IMEP	indicated mean effective pressure
LHV	lower heating value of fuel
$\dot{m}$	mass flow rate
p	pressure
Q_{evap}	evaporator thermal power
Q_1	heat released in combustion
Q	heat
ROHR	rate of heat release
T	temperature, turbine
TXV	thermostatic expansion valve
V	volume
WCOND	water cooled condenser (A/C unit)
ρ	density
γ	politropic coefficient
η	efficiency
θ	Crank angle
ω	engine speed

Subscripts

boost	boost pressure (pressure inside intake manifold)
comb	combustion
g	global
mech	mechanical
therm	thermodynamic
ref	references

lower NOx and Soot [5] and particular focus on NOx decreasing is reported in marine application, too [6]. The effect is so well-known that no turbocharged engine exists without a charge air cooling device (CAC). The same cooling-related benefits are shown in the water injection in the intake line: due to water droplets evaporation, a significantly lower air temperature is achieved, producing a mixture (air and steam) which improves indicated mean effective pressure (i.e brake specific fuel consumption – BSFC [7]) and knock resistance: up to 20% of BSFC reduction is demonstrated for a highly downsized gasoline engine [8] also in comparison with cooled EGR technique [9]. Valuable benefits on the emissions reduction have also been demonstrated for port water injection: the resulted reduction of in-cylinder pressure and temperature lead to a significant NOx and Soot reduction also in 4-strokes Diesel engines [10] and on a 2-strokes ones, with lower influence on p-V diagram [11]. In many cases, the benefits on terms of NOx and fuel combustion reduction are limited by combustion efficiency [12]. Moreover, for HCCI – Homogeneous Charge Compressed Ignition – engines, lower intake temperature extends the operating range of the engine, reducing the knocking intensity and the misfire of the charge [13].

Currently, in turbocharged engines the most used technology to cool intake air after the compression stage is an air cooled heat exchanger placed on the intake line. A recent developed technology uses water to cool down the intake air [14], by means of a low temperature coolant loop in a double temperature engine cooling layout [15]: this configuration demonstrates benefits also on the overall thermal management of the vehicle (opening to a re-design of the cooling paths inside the engine block and head [16]) and significantly reducing the engine warm up time, up to 30% in a passenger car [17]. More recently, the research focused on the exhaust gases heat recovery to feed cooling-dedicated components, e.g. air cooling below ambient temperature using the heat from exhaust gases to feed a jet ejector cooling device [18,19]. Major issues to address with reference to this solution are system scalability (i.e. components packaging, down-sizing and down-weighting) and integration with present engines configuration: the benefit associated with the waste heat recovery should be compared to the detrimental effect of a higher induced engine backpressure [20], as well as the additional fuel consumption to drive a compression chiller, which is not necessarily compensated by the benefit of charge-cooling, especially in presence of unsteady operating regimes for the engine. Other approaches address the achievable potential improvement through the charge cooling via a heat pump [21], or a mechanically driven compression chiller, whose feasibility should be checked against current trend towards engine down-sizing. Among alternative concepts for a further charge cooling, those ones based on sorption are very interesting: up to 4% of engine indicated efficiency increase have been reported with an absorption refrigeration system coupled to the intake air line [22]; in particular, the adsorption system can be driven by exhaust energy, if the pressure drop on the exhaust is limited [23] and it can meet the cooling request of a coach vehicle [24]. Severe difficulties have been met to control the adsorption system, but it can be easily managed in a range of high engine working points, by controlling the exhaust gases [25]. Low power densities, layout complexity, piping and pressure induced leakages represent a major critical aspect for sorption systems, both in a design phase and during engine operation. Interesting applications have been proposed with an ORC plant used to recover the charge air thermal power before intake manifold, but with still high air temperature after the energy recovery section [26]. Weight increase due to these technologies definitively represents an adverse result which increases propulsion power [27].

Limiting the attention to the present turbocharged air cooling technology, a further cooling improvement could be done using a refrigerating unit on the intake pipe. The presence on board of a vehicle of a conditioning unit for cabin comfort suggests the possibility to use it for this purpose, without particular engine or vehicle modifications. Moreover, in present vehicles the conditioning unit is often over-sized in order to reduce cool-down time of the cabin and it is also under-employed because of its use during hot days. This eventual double function invites to integrate the conditioning unit with the engine cooling system, feeding the condenser of the refrigerating unit with the liquid medium circulating in the low temperature double circuit cooling system [28]. This eventuality would produce a size reduction of the condenser [29], a better performance of the conditioning unit and a simplification of the vehicle's front area [30].

In this paper an IVECO F1C 3 L turbocharged engine has been modified on the intake pipe after the compressor to arrange a conditioning unit, whose evaporator increases the intake air cooling (IAC) with respect to what could be feasible in a conventional engine. The refrigerating unit is fed by an electric motor for sake of simplicity and the power absorbed has been taken into account in order to verify the real benefit on fuel consumption. The evaporator of this unit has been redesigned in order to limit the pressure losses at the air side on the