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A new asymmetric twin-scroll turbine with two wastegates for energy improvements in diesel engines

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HIGHLIGHTS

- A new asymmetric twin-scroll turbine with two wastegates (ATST-2WG) has been firstly presented.
- Experiment and simulation are combined on the diesel engine with asymmetric turbocharger.
- Wastegates control strategy and impact laws of asymmetry are studied.
- The engine with ATST-2WG has the maximum fuel economy improvement of 2.91% compared to the engine with ATST-1WG.

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ABSTRACT

This paper first presented a new asymmetric twin-scroll turbine with two wastegates (ATST-2WG) for energy improvements. An asymmetric twin-scroll turbine with one wastegate (ATST-1WG) is relatively simple and can effectively solve the contradiction between low nitrogen oxide emissions and low fuel consumption when exhaust gas recirculation is employed. However, its disadvantage is that the fuel economy will decrease at a partial opening degree of the exhaust gas recirculation valve, especially at a high-speed engine range. An experimental investigation has been performed to calibrate the numerical model of a diesel engine equipped with an asymmetric twin-scroll turbine with one wastegate, and the engine with an asymmetric twin-scroll turbine with two wastegates model has also been especially established. Based on the models, both the wastegates control strategy and the critical parameter ASY turbine asymmetry (ASY, the ratio of the throat areas of the two scrolls) effect laws have been studied, and they are different from the asymmetric twin-scroll turbine with one wastegate. The brake specific fuel consumption advantage first remains unchanged and then decreases as the engine speed increases, and the maximum fuel economy improvement is 2.91% at the rated power point. The asymmetric twin-scroll turbine with two wastegates has great advantages to achieve a better balance of engine emissions and energy.

1. Introduction

Internal combustion engines are widely used and play an important role in industry. During the last two decades, engines have consumed a large amount of fuel and led to considerable environmental pollution. At present, energy conservation and emission reduction are essential with greater energy shortages and environmental problems being, especially in the automobile and marine industries [1,2]. Since the Corporate Average Fuel Economy (CAFE) was first established in the United States in 1970s, the standards to improve fuel economy have been spreading worldwide [3,4]. The Euro 6 nitrogen oxide (NO_x) limit for diesel cars is 80 mg/km, a reduction of over 95% compared to Euro 1 emissions legislation [5,6]. Euro 6-compliant diesel passenger cars feature lean NOx traps to satisfy the increasingly stringent NOx regulations [7]. It is hard for the automakers to secure an optimal portfolio of fuel-efficient and emission reduced technologies that complies with tighter emission regulations and addresses rising fuel costs. The strengthened standards have driven engine manufacturers to use exhaust gas recirculation (EGR) and turbocharger technologies in an ever-increasing number [8].

EGR is a well-accepted method to transport a fraction of exhaust gas back to the combustion chambers. Exhaust temperature is the key factor and the facet effect for diesel engine NO_x emissions [9,10]. EGR decreases the oxygen fraction inside the chambers as well as the peak temperature during the combustion processes, so it effectively reduces NO_x in the research of Raptotasios et al. [11] and Zhong et al. [12]. The

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Nomenclature

φ	turbine throat area
rpm	revolutions per minute
rps	revolutions per second

Subscripts

1	small scroll inlet
2	large scroll inlet

Abbreviations

ASY	turbine scroll asymmetry
ATST	asymmetric twin-scroll turbine
ATST-1WG	asymmetric twin-scroll turbine with one wastegate
ATST-2WG	asymmetric twin-scroll turbine with two wastegates
BSFC	brake specific fuel consumption
C	compressor
DI	direct injection
DL	dual loop
EGR	exhaust gas recirculation
HP	high pressure
LP	low pressure
NO_x	nitrogen oxides
OPD	the opening degree of the EGR valve
PMEP	pumping mean effective pressure
RES	the relative engine speed
STST	symmetric twin-scroll turbine
T	turbine
VGT	variable geometry turbine
WG	wastegate

EGR rate, defined as the mass percent of the recirculated exhaust in the total intake mixture, is the general parameter controlled by the position of the EGR valve. In a proper range, NO_x decreases with the increasing EGR rate. Ref. [13] investigated the effects of the proportion of high pressure and low pressure (HP/LP) EGR on engine operation. HP EGR systems are most common for turbines, whereby exhaust gas is drawn from upstream of the turbocharger. EGR and turbocharging system control offers broad potential to lower NO_x emissions and fuel consumption; the control reduced NO_x emissions above 50% compared to Euro 5 levels [14]. Wei et al. [15] concluded that EGR techniques can reduce engine fuel consumption and meet more stringent emission regulations in addition to other advanced techniques. At present, many turbocharging technologies, including two-stage turbocharging, variable geometry turbines (VGT), symmetric twin-scroll turbines (STST) and ATST-1WG are widely combined with EGR in diesel engines.

To further increase waste energy recovery and improve engine performance, two turbochargers of different sizes can be connected to form a two-stage turbocharging system. In a two-stage turbocharging system, the HP turbocharger is smaller than that of the LP in order to achieve a better transient response at low speeds; the LP turbocharger is large and is optimized for maximum power output operation [16]. Single-stage turbocharging does not typically maintain high boost pressure and a heavy EGR rate due to limited overall turbocharging efficiency, especially at low-speed engine ranges [17]. Therefore, two-stage turbocharging is widely adopted for vehicles and small aircrafts [18]. Compared with single stage turbocharging, two-stage turbocharging provides flexibility to meet engine requirements at both low and high speeds because of load split. Both LP and HP stages can operate at reduced flow and pressure ratio ranges. However, two-stage turbocharging has more complicated mechanical structures and control systems to achieve smooth operation during stage switching. The performance accuracy measurement for mapping turbocharging systems in steady turbocharger gas-stands is difficult to ensure due to aero-thermal inter-stage phenomena [19]. The disadvantages of two-stage turbocharging are complicated piping, valve and seal systems, and a considerable weight penalty. Two-stage turbocharging systems also have larger flow passage volume and more metal surface than single stage systems, and this can affect the time taken by the turbocharger to warm up from the cold start, thus affecting the operation of the downstream catalyst converter and engine cold start emissions [20].

The most widely recognized problem with fixed geometry devices is turbocharger lag, which is the poor transient response of the turbocharger at low engine loads [21]. Therefore, VGT is a well-accepted and potential technology to increase boost-pressure at low speeds and reduce response times [22]. VGT can change the turbine throat area and provide enough backpressure to drive EGR and allows good handling of fuel injection and inlet air charge flow into the combustion chamber [23,24]. In VGT devices, the aspect ratio will determine the EGR flow, and the EGR rates are fixed by adjusting the VGT position, since it governs the pressure difference between the inlet manifold and exhaust manifold [25]. Therefore, EGR and VGT are combined to control and optimize the fuel consumption by minimizing pumping losses [26,27]. VGT offers improved turbocharger rotational speed, engine speed and boost-pressure over a regular turbocharger and allows the performance of the turbocharger to be optimized across the whole engine range [28,29]. Furthermore, the trend of actuating VGT devices is shifting further towards electrical and hydraulic variants that allow more delicate control than pneumatic controls. Variable two-stage turbocharging systems that may regulate exhaust enthalpy and matching points to the high efficient zone under different operating conditions will be widely used [16]. However, VGT has very sophisticated control systems to match with the EGR system and the engine system. The strength and reliability of the adjustable vanes are very fundamental [30], and the vanes are expensive. In the same production volume, the cost of a typical VGT ranges from 270% to 300% of the cost of the same size system and can offer gains of approximately 20% over comparable fixed geometry turbocharger systems [31].

The twin-scroll turbine is a meridionally divided turbine, and the scroll has a single divider around the entire perimeter of the housing. Each inlet feeds the entire rotor circumference. It was first proposed in 1954 [32,33]. The STST, which has two inlet scrolls whose shapes and areas are uniform, has traditionally seen wider use on multiple-cylinder engines by turbocharger manufacturers due to its inexpensive and simple design. A comparison between the twin-scroll (meridionally divided) and double-scroll (circumferentially divided) turbines revealed their very distinct efficiency characteristic [34]. A double-scroll turbine has been shown to deliver higher peak efficiency at full admission conditions. Therefore, a twin-scroll turbine showed lesser deterioration at partial admission conditions because the flow was still capable of expanding into the larger rotor inducer area, even though not entirely [35,36]. Chiong et al. [37,38] presented a revised one-dimensional pulse flow modeling of twin-scroll turbocharger turbine under pulse flow operating conditions. The results showed that a twin-scroll turbine does not operate at full admission throughout the in-phase pulse flow conditions. Instead, the turbine worked at an unequal admission state due to the magnitude disparity of the turbine inlet flow. Rajoo et al. [39] discussed the details of unsteady experimentation and analysis of a twin-scroll variable geometry turbine for an automotive turbocharger. The cycle-averaged efficiency of the twin or single-scroll nozzled turbine was found to depart significantly from the equivalent quasi-steady. In comparison to the nozzleless single-scroll turbine, the departure was as much as 32%. When STST is used to drive EGR, both two-exhaust