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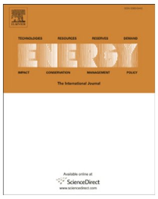

Characterization of two-stage turbine system under steady and pulsating flow conditions

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ABSTRACT

As the development of turbocompounding and two-stage turbocharging technology, there are increasingly more two-stage turbine systems applied on vehicles. The two-stage turbine recovers waste heat from the exhaust and thus affects the engine performance significantly. However, the interaction pattern and mechanism between the two turbines have not been fully understood. The paper focuses on the characteristic of the two-stage turbine under steady and pulsating flows.

Firstly, an analytical model for two-stage turbine is developed to investigate the relationships between the turbines load split and equivalent area ratio under steady condition. The pattern of the load split between the high pressure turbine (HPT) and low pressure turbine (LPT) is disclosed by the model and verified by experimental data.

Second, the impact of pulse frequency and amplitude on the two-stage turbine unsteady characteristic is studied by 3D computational fluid dynamics. As frequency increases, the peak values of the HPT expansion ratio and rotor torque increase drastically while those of LPT change little. As the pulse amplitude increases, the cycle-averaged expansion ratio of HPT decreases while that of LPT increases. The cycle-averaged rotor efficiencies of HPT and LPT reduce 3.7% and 8.1% respectively under 1.6 A amplitude condition, when compared with steady condition. In order to understand the phenomenon, the reasons are also discussed in detail in the paper.

1. Introduction

With increasingly stringent regulation on fuel saving and emissions reduction of internal combustion engine, turbocompounding and two-stage turbocharging technologies draw wide attentions from academic and industry area.

Continuous improvements in the turbocharger (T/C) efficiencies over the past decades have made it possible for the exhaust stream to have surplus energy than required for compressing process during normal engine load conditions. The excess energy can be harvested by turbocompounding, including mechanical, electrical and hydraulic turbocompoudning [1]. In general, turbocompounding an engine improves the fuel economy with low volume and weight requirements. It enables the engine to achieve retarded ignition timing, higher EGR driving capability, and better response at transients, as well [2]. In a typical turbocompound engine, a power turbine is placed downstream the conventional turbocharger turbine. As a result, the pumping loss of the engine will increase significantly. Therefore, the design of the turbcompound engine must be careful to obtain lower fuel consumption [3]. To further increase fuel saving potential, turbocmpounding combined with VGT [4] or steam injection [5] was also proposed by Zhao.

The current studies on turbocompounding mainly focused on the matching, design and control of the low pressure power turbine, instead of the two-stage turbine systems. For example, Katsanos [6] investigated the rotating speed of the power turbine on the engine fuel performance at off-design conditions and obtained the optimum power turbine speeds. Briggs [7] focused on the

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Nomenclature

Latin symbols

A	equivalent turbine flow area (m^2) or amplitude
c_p	specific heat ratio at constant pressure (J/kg K)
f	frequency(Hz)
h	enthalpy (J/kg)
i	number of cylinder
$\dot{m}$	mass flow rate (kg/s)
N	Reduced speed (rpm/K$^{0.5}$)
n	rotation speed (rpm)
p	pressure (Pa)
R	degree of reaction
R_g	gas constant (J/kg K)
r	radius (mm)
T	temperature (K) or pulse period (s)
t	time (s)

Acronyms

AR	area ratio
BSR	blade speed ratio
bmep	brake mean effective pressure (bar)
CFD	computational fluid dynamics
EXP	experiment
HPT	high pressure turbine
LPT	low pressure turbine
MFP	mass flow parameter $\dot{m}\sqrt{T_{t,in}}/p_{t,in}$
T-T	total to total
T-S	total to static
VGT	variable geometry turbine
WGT	waste-gate turbine

Greek symbols

γ	adiabatic exponent
η	efficiency
π	expansion ratio
τ	torque (Nm) or stroke number
φ	coefficient
ω	angular velocity (rad/s)
Δ	variation

Subscripts and superscripts

1–5	locations in the two-stage turbine
ave	average
c	critical
ex	exit
h	high pressure turbine
in	inlet
inst	instant
l	low pressure turbine
r	rotor
s	stator
t	stagnation condition

impact of rated power of the power turbine on the engine overall performance and 2.4% reduction in fuel consumption was observed. Mamat [8,9] designed a power turbine with ultra-low expansion ratio for turbocompounding. Zhao [10] analyzed the effects of power turbine geometric parameter on the turbocompound engine performance by a throughflow model. These studies focused mainly on the power turbine while did not treat the two-stage turbine as a whole. Actually, both the turbocharger turbine and power turbine associates with the waste heat recovery in the exhaust. However, the interaction mechanism between the two turbines is not clear.

As for two-stage turbocharging, it has the potential to facilitate downsizing of automotive engines in order to yield benefits in terms of their transient performance, fuel consumption and emissions output [11]. Serrano [12] presented a two-stage turbocharged heavy-duty diesel (HDD) engine designed to fulfil stricter regulation. It was found that a two-stage turbocharging configuration could greatly improve engine drivability and reduce NOx emissions during transient evolution. Yongsheng [13] adopted two-stage turbocharging in a Miller cycle engine to compensate the torque loss due to late intake valve closing or early intake valve closing. The experimental results indicated that this engine concept could improve the fuel economy of the vehicle by 3–4% at typical city and highway driving conditions while maintaining the same power performance. In the study of Shi [14], two-stage turbocharging was applied to compensate the power loss at high altitudes. With two-stage turbocharging, the engine power output could remain the same as that at sea level up to 2000 m and it could be recovered to 80% at 5500 m. Liu [15] compared the performance of two-stage turbocharged engine with single-stage turbocharged engine at altitude of 5500 m. It was found that with the two-stage turbocharging, the rated power and maximum torque increased by 48.2% and 51% separately, the minimum fuel consumption decreased by 12.6%.

The benefits of two-stage turbocharging are significant while the design and matching of the two-stage turbocharger is a sophisticated process. Galindo [16] discussed the impacts of the LP and HP turbine expansion ratios on the engine overall performance based on an analytical model. The optimal expansion ratios of the two turbines were obtained in the study. However, how to match the two turbines to achieve the designed expansion ratio was not presented. In engineering practice, different turbine maps are inputted into the engine simulation model for performance evaluation. Iterations are required to obtain the optimum pressure ratio or the best engine performance. To reduce iteration time, different matching methods are proposed. Shan [17] introduced a simulation method for gas turbine engine with component models, based upon component maps and algebraic equations. This method converged rapidly that it needed only 5–6 iterations to obtain one operating point. Yanbin [18] suggested a matching method for two-stage turbocharging system beginning from turbines matching. Matching results proved that this method could raise the turbine system efficiency in whole operation points, when compared with traditional method. Cui [19] presented a theoretical optimization design process for a Miller-cycle regulatable, two-stage turbocharging system for marine diesel engines. The high- and low-stage turbochargers were selected by an iterative matching method. To solve the matching problem in different altitudes, an equivalent matching model was proposed by Hualei [20]. It revealed the relationship between the matching speed, the pressure ratio distribution, the bypass flow rate ratio and the plateau adaptability. Although these methods improved the efficiency of the two-stage turbine matching, they rarely discussed the relationship between the two turbines. In other words, the studies mainly focused on the relationship between the turbine and engine. Yang [21] studied the influence of altitude on the performance of a regulated two-stage