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Multi-field coupling dynamic modeling and simulation of turbine test rig gas system

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ABSTRACT

On the basis of early research on the 38-component system, this paper extends the established finite volume model to the multi-field coupling numerical system which can describe flow, heat transfer, combustion and rotation, and conducts, based on the experiment, dynamic modeling and simulation research on the turbine test rig gas system which includes turbine and load. The comparison among the simulation results, test data and early simulation results indicates the 42-component system established by this paper has made improvements against many weaknesses of the Previous simulation in an all-round way. Accordingly, it can be concluded that the case setting and algorithm improvement are effective. It is also found that the modeling of module with chemical reaction, the spool throttling modeling of various regulator valves, the modeling of the turbine characteristics and the modeling of wall heat transfer are four key factors which affect simulation accuracy, and that the coupling modeling of flow and combustion is the key factor which affects simulation stability.

1. Introduction

The idea of modularization [1] is gradually formed to meet the demand of versatile system modeling. Its basic idea is firstly viewing the system as an assembly of some typical components which are called modules, secondly establishing numerical model of every module and encapsulating it as an independent function module, finally establishing numerical model of the whole system by combination of relevant modules according to special rules. As all components of the same type are described by one module, the modeling and simulation problem of all kinds of systems with different structures can be solved conveniently by computer. In the liquid propulsion system (LPS) simulation field, this idea is deemed to be put forward by A.P. Tishi and L.P. Gurova [2]. Since late 1980s, relevant researches have been evolving toward maturity and put into application in the form of simulation software [3–25]. Ref. [26] summarizes the relevant researches and points out that future improving direction in the aspect of algorithm will focus on more detailed and accurate modular modeling of typical component, and integration of simulation and optimization function for optimization application.

At the level of component research, the high-fidelity full-scale three-dimensional (3D) or two-dimensional (2D) modeling and simulation can be conducted by employing the leading CFD (Computational Fluid Dynamics) software tools (e.g. CFX, FLUENT) for many components of LPS. However, at the level of system research, that has not become the mainstream practice mainly because: for a transient complex system consisting of tens of or even hundreds of components, the CFD softwares

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Nomenclature

A	cross-sectional area (m^2)
A_{bmin}	the smallest flow section area of turbine stationary blade nozzle (m^2)
a_{cr}	critical sound velocity (m/s)
C_d	flow coefficient
C_{sb}	flow coefficient of turbine stationary blade nozzle
c_p	specific heat at constant pressure (J/(kg K))
D_{TM}	turbine cascade average diameter (m), $(D_{hub} + D_{tip})/2$
E	total energy per unit volume (J/m^3)
f_{mix}	mixture fraction
h	specific enthalpy (J/kg) or spool opening (m)
Ma	mach number
M_{Load}	load torque (N m)
M_T	turbine drive torque (N m)
$\dot{m}$, Q_m	mass flow rate (kg/s)
mr	mean mass mixture ratio
n_{rot}	rotate speed of rotor (r/min)
n_T	rotate speed of turbine (r/min)
P	power (W)
p,p_t	static pressure and total pressure (Pa)
Q_{m_np}	turbine flow capacity parameter
Q_v	volume flow rate (m^3/s)
$\dot{q}$	heat flux density per unit area (W/m^2)
qrho	heat flux density per unit area from in-tube fluid to pipe wall (W/m^2)
qrho2	heat flux density per unit area from wall to out-tube fluid (ambient atmosphere) (W/m^2)
R	specific gas constant (J/(kg K))
Re	Reynolds numbers
r	pipe-wall radial coordinate or radius (m)
r_{Q_m}	the mass-flow-rate ratio of oxidant to fuel flowing into combustion zone
S	surface area (m^2)
T, T_t	static temperature and total temperature, respectively (K)
T_{f_2}	fluid static temperature outside the pipe (ambient temperature) (K)
t	time (s)
u	fluid velocity in x direction (m/s)
u_{TM}	median-location circular velocity of turbine blade (m/s)
V	volume (m^3)
W	work per unit mass working medium (J/kg)
x	axial direction of pipe (one-dimensional flow direction)
α_2	coefficient of convective heat transfer from pipe wall to out-tube fluid ($W/(m^2 K)$)
γ	ratio of specific heat capacities of gas
ε_1, ε_2	blackness of pipe wall and ambient environment, respectively
ε_s	system blackness
η	efficiency
λ	thermal conductivity (W/(m K))
λ_u	median-location circular velocity coefficient of turbine blade
π	circular constant
π_{pt}	turbine total pressure ratio
ρ	density (kg/m^3)
σ_0	blackbody radiation constant ($W/(m^2 K^4)$)
τ	valve relative opening
Ω_T	turbine reaction degree
ω	rotational angular velocity (radians/s)

Subscripts

ad	adiabatic
c	combustion zone
ektexine	external surface of pipe wall
f	fluid
f	fuel
i	serial number of a axial-direction grid