INTERNATIONAL JOURNAL OF HYDROGEN ENERGY XXX (2017) 1–11

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journal homepage: www.elsevier.com/locate/he

Review of engineering solutions applicable in tests of liquid rocket engines and propulsion systems employing hydrogen as a fuel and relevant safety assurance aspects☆

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ARTICLE INFO

Article history:
Received 24 June 2017
Accepted 30 June 2017
Available online xxx

Keywords:
Rocket engine
Power plant
Testing
Safety
Simulation
Hydrogen
Diagnostics
Emergency protection system

ABSTRACT

The review presents the author's papers on specific features of experimental development of oxygen-hydrogen liquid rocket engines (LRE), namely the 11D56, 11D57, RD0120, KVD1, and a number of propulsion units and power plants, as well as compares some data on propulsion development activities with relevant data obtained abroad. Also has been shown a role of model studies, component-level tests of engine units and systems, including those performed at simulated flight conditions, and integrated tests in support of experimental development of advanced engines and propulsion systems designed for rocket upper stages. There have been considered techniques and equipment intended to ensure safety of ground testing of rocket engines and power plants involving the use of effective diagnostic systems and emergency protection systems.

Introduction

Critical issues associated with producing of hydrogen rocket engines include: characterization of the most overloaded (stressed) LRE units and components, elaboration of effective emergency protection channels and methods of engine diagnostics, simulation of flight conditions and safety assurance of test operations.

Development of LOX/LH$_2$ engines 11D56 and their upgraded versions 11D57, RD0120, KVD1 and RD0146D

The first rocket engines RL-10 (with a thrust of 68 kN) and J-2 (with a thrust of 1020 kN) employing oxygen/hydrogen propellant combination were built in USA in the sixties of the 20th century. But it should be noted that studies of hydrogen application as a rocket fuel began in the USA at the initiative of the Department of Energy as early as in 1944.

☆ This paper is the English version of the paper reviewed and published in Russian in International Scientific Journal for Alternative Energy and Ecology "ISJAEE", issue 176, number 12, date 15.07.2015.

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http://dx.doi.org/10.1016/j.ijhydene.2017.06.242

Nomenclature

Greek Letters
τ time (to retardation inflammation), s

Latin Letters
d diameter of nozzle, m
f the expansion ratio of the nozzle
$\dot{m}$ the mass flow per second, kg/s
m mass (of the hydrogen emission), kg
p pressure (in combustion chamber), MPa
Δp shock wave (of detonation), kPa
q rate buildup gradient, $\frac{kg/s}{s}$.
T Temperature, K
z coefficient of hydrogen involvement in explosion

Acronyms
CC Combustion chamber
GG Gas generator
LPE Liquid-propellant engine
PS Propulsion system
NITs RKP The Rocket and Space Industry Research and Test Center
RSS Rocket-space system
TPU Turbo-pump units
ISMAN Institute of Structural Macrokinetics Russian Academy of Sciences
KBKhM Isayev Design Bureau for Chemical Engineering
KBKhA Design Bureau for Chemical Automation
PJSC "Cryogenmash" Public Joint Stock Company of Cryogenic Engineering
RSC Energia S.P. Korolev Rocket and Space Corporation Energia
TsNIIMASH Central Scientific-Research Institute of Machine Building
VIAM ALL-Russian Institute of Aviation Materials
MAI Moscow Aviation Institute
GKNPTs Khrunichev State Research and Production Center
NPO IT Research and Production Association for Measurement Technology
NPO Tehnomash Research and Production Association for Engineering Machine Building

Superscripts and subscripts
CC Combustion chamber
GG Gas generator
start start
a the output cross section of nozzle
e ejection
d delay (of ignition)

In our country a possibility of using oxygen/hydrogen propellant for upper stages of N1-L3 rocket was taken into consideration in the sixties last century. Related activities aimed at developing oxygen/hydrogen LRE 11D56 with a thrust of 73.5 kN and the 11D57 with a thrust of 392 kN started in the EDB (experimental design bureau) named after A.M. Isaev and in the EDB named after A.M. Lyulka back in 1962. Those engines were meant to be used during a subsequent upgrading of the rocket systems.

In support of experimental development and verification of above mentioned engines there was constructed an appropriate oxygen/hydrogen test facility on site of the Scientific and Research Institute of Chemical Machine Building (Russian acronym is NIICHIMASH, a former designation of FKP NIC RKP) allowing the systems approach to developing entire engines and individual components running on real propellants. The test facility included a number of test stands designated as B1, B2, B3, B4 and B5. In the years 1962 through 1967 the test stands B1a and B1b were used for experimental development of thrust chambers, gas generators, turbopump units and engines 11D56 and 11D57 in short-term closed circuit tests. The author of this review had been involved in ground development tests of the 11D56 and 11D57 engines and their modifications since 1964, acting as a head of B1 test bench. These development efforts included sub-scale tests of engine elements, units and systems, component-level tests and engine-level tests. Based on those research activities and technically proven solutions the author defended his Ph.D. theses in 1974 [1].

Early phase engine-level tests are usually carried out without reproducing real operating conditions in oxidizer and fuel feed lines upstream of an engine, and high-altitude conditions at the engine nozzle exit, as well. Final phase engine-level tests called for using dedicated facility hardware to provide simulation of actual operating conditions, including starting tanks in the facility feed lines and exhaust diffusers with evacuating units installed in the engine exhaust duct which were used in ground-based development tests of the 11D56, 11D57 engines and their upgraded versions [2].

Full-scale firing tests of an engine integrated in a propulsion system were usually preceded by cold flow tests of that propulsion system to check and verify propellant filling, pressurization, discharge (drain) operations and expulsion from propellant tanks, tank heat insulation systems, flow rate and mixture ratio control systems, engine feed lines chill-down processes [3].

Later, above mentioned test stands were used, with participation of the author, for experimental verification of nuclear rocket engines 11D410, the LRE RD0120 (Energia launch vehicle), LRE KVD1 (GSLV launch vehicle under a cooperation contract with India), propulsion systems of cryogenic stages of GSLV and Energia LV [4–12], magnetohydrodynamic generator systems employing oxygen-hydrogen propellant with the ionizing additive of a potash-sodium eutectic [13,14], thermal-protective composite carbon-carbon materials for descent vehicle lead units exposed to LRE high velocity jet [15,16].

Component-level development of the RD0120 engine (thrust chamber, turbopump unit, gas generator) was conducted for the most part on B2 test bench by means of engine firing tests (74 tests all in all).

In view of lack of a full-scale test bench early phase integrated tests of the RD0120 engine aimed at design optimization were conducted with a gradual increase in thrust level (20%, 50%, 75% and 100%), which resulted in a longer development time and the increased overall number of engines to undergo development tests. The second phase of engine