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Transient simulation of a differential piston warm gas self-pressurization system for liquid attitude and divert propulsion system

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Abstract In order to obtain the dynamic characteristics of a differential piston warm gas self-pressurization system for liquid attitude and divert propulsion system, a transient model is developed using the modular modeling method. The system includes the solid start cartridge, pressure-amplified tank with liquid monopropellant, liquid regulator, gas generator, and pipes. The one-dimensional finite-element state-variable model is applied to the pipes and the lumped parameter method is adopted for the other modules. The variations of the system operation parameters over time during the startup, steady-state, and pulsing operational processes are obtained from the transient model, and the characteristics of starting time changing with different system parameters are also analyzed. It is shown that the system startup process can be divided into three distinct processes. The starting time monotonically changes with variations of the liquid regulator parameters, first decreasing and then increasing with the mass change of the solid propellant charge of the start cartridge, initial gas cavity volume of the pressure amplified tank and initial gas cushion of the propellant tank. The starting time can be reduced to less than 1.0 s (0.68–0.75 s for the current system). For meeting the deviation requirements of ±10% of the steady-state propellant tank pressure, the positive deviation requirement is assured by the self-locking pressure and the negative deviation can be assured within an allowable maximum propellant tank volume flowrate (1.6 times the design value for the proposed system) for downstream thrusters for a designed system. The results from the simulation are useful as a guide for further system design and testing.

1. Introduction

The function of the Differential Piston Warm Gas Self-Pressurization System (DPWGSPS) is to generate warm gas for tank pressurization via catalytic chemical reactions of the liquid monopropellant for the liquid attitude and divert propulsion system. In comparison to typical cold gas

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pressurization systems, the DPWGSPS can significantly reduce both the weight and volume, eliminate gas storage requirements, and enhance the safety and reliability.[1] The technology has attracted attention in recent years as a candidate for a number of applications including rockets, spacecraft, and missiles.

A monopropellant DPWGSPS applying M-75 (hydrazine/MMH blend) was developed and tested in 1998 by the Primex Aerospace Company, which was designed to pressurize propellant tanks and provide a regulation band of 5.8 MPa + 5%/−7%.[1] Around the same time, a conceptual study of the DPWGSPS utilizing high-test peroxide as the monopropellant medium was carried out by the Lawrence Livermore Nation Laboratory.[2–4] Further to this, a parameter design method on the DPWGSPS was developed by the authors.[5] The DPWGSPS has several advantages over typical propulsion systems such as improved pressurization efficiency, low system mass, and small envelope size.[6]

Numerous studies on the dynamic models and simulation methods of Liquid Propellant Engine (LPE) have been carried out. Ruth et al.[7] introduced a liquid rocket transient code, which modeled the engine as a modular scheme and used the method to characterize the flow through line segments connected by nodes. Binder[8] developed steady-state and transient computer models of the RL10A-3-3A rocket engine using a transient simulation code. Liu and Zhang[9] developed a pipe-volume disassembly method for fluid line systems. In their method, fluid line systems were disassembled into pipe-type modules and volume-type modules. The finite-element state-variable model was applied to the former, and the lumped-parameter method was applied to the latter. Karimi et al.[10] proposed a dynamic and nonlinear simulation method for LPEs, which composed the dynamic equations to the implicit nonlinear algebraic equations, nonlinear and time-varying differential equations. Yamanishi et al.[11] used a rocket engine dynamic simulator, based on the volume-junction method for the transient analyses of the LE-7A engine. A simulation algorithm adapted from the Newton–Raphson method was reported by Karimi and Nassirharand[12] and used for the dynamic and nonlinear analysis of a LPE. Moreover, a VINCI engine transient model was introduced by Durteste[13] and used to predict the global behavior of an engine. Zanj et al.[14] developed a nonlinear modeling and dynamic simulation of a hot pressurization system to estimate the pressure, temperature, and mass flowrates of pressurant and propellant during the expulsion from a tank. Three semi-empirical models were introduced by Di Matteo et al.[15,16] to improve the European Space Propulsion System Simulation (ESPSS) library as a system modeling tool for transient analysis, and an LPE transient model was developed to simulate the startup transient and the model was then validated using the RL-10. Tabrizi et al.[17] modeled major elements and developed a general simulator for an open cycle LPE. Liu et al.[18] investigated an LPE model library in the Modelica language containing component models. Lin and Baker[19] employed a characterization method to model one-dimensional liquid transients in liquid-full segments and the lumped-inertia technique to model the dynamics of partially filled segments in order to analyze the priming of a propellant feed system. Holt et al.[20] developed a transient model of a propulsion test article helium pressurization system using a generalized fluid system simulation program.

While numerous advances have been made in modeling typical propulsion systems, to the authors' knowledge there has been little research on the transient simulation of DPWGSPSs. In order to guide further system design and testing, it is necessary to conduct the system transient simulation. The methods in aforementioned references, such as the system's modularization modeling method, the pipe-volume disassembly method, the finite-element state-variable method, and the lumped-parameter method, are useful for current research.

The objective of this work is to develop an integrated mathematical model for the DPWGSPS to predict the variation in pressure and pressurization flowrate over time during the system startup, steady-state, and pulsing operations, and to further analyze the characteristics of starting time changing with different system parameters.

2. Physical model

A schematic of the DPWGSPS is presented in Fig. 1. It consists of a Start Cartridge (SC), a Pressure Amplified Tank (PAT), a Liquid Regulator (LR), a Gas Generator (GG), a Check Valve (CV), Burst Disks (BD), Gas Joint (GJ), Gas Pipes (GP) and Liquid Pipes (LP). In particular, when the liquid is filling the pipe during the system startup, this pipe is also defined as a Filling Pipe (FP).

The DPWGSPS is initiated by an electrical signal provided to the initiator of the SC, which ignites the solid propellant and produces warm gas. A hermetic seal is ruptured allowing warm gas from the SC to pressurize within the gas cavity of the PAT and the differential piston within the PAT pressurizes the monopropellant (hydrazine-70). Then, a burst disk at the PAT outlet ruptures and the monopropellant is sent through the pipe and LR into the GG which decomposes the monopropellant into warm gas, thereby pressurizing the gas manifold and propellant tanks. The SC continues to provide warm gas to the gas cavity of the PAT until the solid propellant charge is burnt out.

During the process, the CV near the inlet of the PAT prevents the SC gases from entering the gas manifold, GG, and propellant tanks. The regulator will close at its locking pressure at the end of startup and the propellant tanks will lock up near this pressure. The system enters the self-locking state and the startup is completed.

Once the downstream rocket engines are ignited, the propellant tank pressure falls and the outlet pressure of the LR is reduced to below the nominal set point. This causes the LR open allowing monopropellant to enter the GG, which again decomposes the monopropellant to warm gas for pressurizing the propellant tanks. Simultaneously, as the gas cavity pressure of the PAT reduces, the CV will open, when the pressure is lower than the pressure of CV inlet (gas manifold), and the gas produced by the GG through the CV pressurizes the gas cavity of the PAT. The amplification ratio of the PAT provides the positive feedback needed for continuous system operation, and the LR regulates the pressure at its outlet to provide the overall pressure reference. When there is no further demand, the regulator closes and the system is returned to the lockup condition.

The LR and CV maintain stability of the pressure within the system. The LR is a self-maintaining component, which

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