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# Dynamic modeling and simulation of a pressurized system used in flight vehicle

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**KEYWORDS**

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Stability

**Abstract** For a typical pressurized system with a novel dual-stage gas pressure reducing regulator, a system model is established with modular models of various typical components. The simulation study on the whole working period shows that the general trends and magnitudes of simulation curves are in agreement with experimental measured curves. As the key component in the pressurized system, the regulator is studied by a series of numerical simulations to reveal the influences of various structure parameters on its stability. Furthermore, the variable ranges which can guarantee the stability of regulator and system are obtained to provide guidance for design. The modeling and analysis approach can be applied to other systems and components.


## 1. Introduction

As a part of propulsion system in aerospace flight vehicle, the pressurized system generally involves high-pressure gas vessel, pressure reducing regulator, valve and other attached pipes. By delivering the pressurized gas stored in gas vessel into the propellant tank with designed pressure, the system can control the ullage pressure of propellant tank, and guarantee that the propellant is supplied to engine pump or combustion chamber with designed pressure and flux.

Numerical simulation, as a research approach in addition to experimentation, can shorten design and development time, reduce experimental costs and provide guiding advice for experiments. Many researchers conduct simulations on different pressurized systems. Matsumoto et al.[1] proposed a new self-pressurized system for propellant feed system so as to reduce the system weight. The steady mathematical model was established and verified to describe the system behavior. Karimi et al.[2] simulated a pressurized system in upper stage engine. It had a special capsule stored by high-pressure gas. The simulation results proved that the heat exchanger installed in front of the tank can improve the performance of pressurized system. They[3] also conducted simulation on a warm pressurized system, and a simultaneous simulation approach was verified. Li et al.[4] studied a pressurized feed system of the dual-thrust hybrid rocket motor. The influences of some structure parameters and initial state parameters on the performance of motor were obtained. Guo et al.[5] conducted an investigation on a gas cycling test system. The simulation

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**Nomenclature**

$A$, $A_v$ cross-sectional area
$A'_{I0}$, $A'_{I1}$, $A'_{I2}$, $A'_{I3}$ effective acting area on I-stage valve spool by the fluid of I-stage high-pressure cavity, I-stage low-pressure cavity, and I-stage feedback cavity
$A'_{II0}$, $A'_{II1}$, $A'_{II2}$, $A'_{II3}$ effective acting area on II-stage valve spool and diaphragm by the fluid of II-stage high-pressure cavity, II-stage low-pressure cavity, and II-stage feedback cavity
$Ac_{I3}$ effective acting area on I-stage valve spool by the fluid of I-stage spring cavity
$Ac_{II2}$, $A'_{II4}$ effective acting area on II-stage valve spool by the fluid of II-stage deputy feedback cavity
$A'_{mII}$ effective acting area on diaphragm by the fluid of II-stage spring cavity
$C$, $C_{mII}$ spring and diaphragm stiffness
$C_d$ flow coefficient
$c_p$ specific heat at constant pressure
$d$ pipe inner diameter or equivalent diameter
$d$c valve rod diameter
$d_{gII}$, $d_{mII}$ diaphragm hard-core diameter and fixed edge diameter
$d_v$ valve seat/hole diameter
$E$ total energy per unit volume
$e$ internal energy per unit mass
$f_x$ force per unit mass along $x$ direction
$f_\lambda$ dimensionless friction loss coefficient
$f_R$ damping force along $x$ direction
$g$ gravity acceleration
$h$, $h_{max}$, $h_{vII4}$ valve spool opening, maximum opening, and the distance between diaphragm and shell
$h_d$ moving velocity of valve spool
$l$ equivalent length
$m_{VC}$ valve spool mass
$p$ pressure
$Q_m$ mass flow rate
$\dot{q}$ heat flux density per unit area between fluid and pipe-wall
$r$ pipe-wall radial coordinate or radius
$S$, $S_S$ internal surface area of wall and deformation region
$t$ time
$T$ temperature
$T_f$, $T_w$ temperature of fluid and interior wall
$u$ flow velocity
$u_S$ expansion velocity along pipe-wall outward normal direction resulting from elastic deformation of pipe-wall
$V$, $V'$ pipe grid volume or cavity volume when valve opening is $h$ and 0
$W$ momentum per unit volume
$x$, $x_{II0}$ axial direction of pipe or precompression length of spring, precompression length of diaphragm

*Greek letters*
$\alpha$ cone half-angle
$\beta$ damping coefficient
$\gamma$ specific heat ratio
$\theta$ rotation degree from one-dimensional flow direction to gravity acceleration direction
$\lambda$ thermal conductivity
$\pi$ circular constant
$\rho$ density
$\tau$ relative opening of valve

*Superscripts*
in, out inlet and outlet of grid

*Subscripts*
I, II I-stage and II-stage valve spool
I1, I2, I3 I-stage high-pressure cavity, low-pressure cavity or I-stage main spring, and feedback cavity
II1, II2, II3, II4 II-stage high-pressure cavity or II-stage auxiliary spring, low-pressure cavity or II-stage main spring, feedback cavity, and deputy feedback cavity
atm atmosphere
cI, cII I-stage and II-stage spring cavity
$i$, $j$, $k$ serial numbers of flow-field state element, velocity element and wall radial-direction grid
w, e, s, n western, eastern, southern and northern boundaries of the temperature field grid element
$n$ total number of flow-field grids

results showed that the refueling gas temperature has a significant effect on the stable temperature. Then they[6] designed and simulated a new gas cycling test system by using multi-stage storage and self-pressurized method. The simulation results showed that total energy consumption of the system decreases with the increase of gas storage stages. Among these numerical researches, various simplifications and assumptions are adopted. For example, the system nonlinear factors are ignored[1]; the pressuring gas is considered as ideal gas[2,4]; the component or system is considered as thermal isolation[2]; the kinetic energy and potential energy of the flow are ignored[2,4]; the pipe dynamics is ignored[3,4]; the state parameters in cavity are considered instantaneously uniform[4–6]; the transient opening processes of some valves are ignored.[4]

As an important control component for pressurized system, the pressure reducing regulator can decrease and stabilize the pressurized gas pressure. Since the regulator is a kind of valve, the researches of various valves can be referred to for the study of regulator. Three-dimensional (3D) model[7–12] is widely applied to simulate different valves. Refs.[8–10] conduct simulations on the steady flow field which has definite valve spool opening and boundary condition. It is easy to obtain flow field distribution under different opening, structure or boundary condition. Refs.[11,12] use the dynamic mesh method to calculate the transient flow field with changed opening, and the minimum opening is not zero in order to maintain fluid mesh continuity. Although 3D meshes can model the real structure and 3D model can

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