THERMAL DYNAMICS AND THERMAL MANAGEMENT STRATEGY FOR A CIVIL AIRCRAFT HYDRAULIC SYSTEM

by

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Addressing the growing severe heat-generation and temperature-rise issues of the civil aircraft hydraulic system, this paper proposes a thermal dynamic model and thermal management strategies for the system within full mission profile. Firstly, a new thermal dynamic modeling towards general hydraulic components is conducted. Secondly, thermal dynamic governing equations are derived. Then a thermal management mechanism of the system is proposed. The conducted research is prerequisite to future numerical simulation of the thermal dynamic characteristics, evaluation and improvement of thermal management strategies for the system.

Key words: *civil aircraft hydraulic system, thermal dynamics, modeling, temperature-rise, thermal management*

Introduction

The hydraulic system in civil aircraft plays an important role for power transmission and actuating control of flight control surface, landing gear and other aircraft loads within the full mission profile [1]. To control the temperature of the hydraulic oil in an allowable range is very necessary for guaranteeing reliability and safety of civil aircrafts [2]. Because the hydraulic system inevitably concerns with various power losses, external heat radiation, heat convection, and the friction between civil aircraft skin and its ambient air during the process of the flight [3], the converted heat is absorbed by hydraulic oil and components, and finally causes the increase in the temperature of the hydraulic system. In recent years, with the development of high pressure, large-power and more-electrification of the aircraft, the temperature issue has become more serious [4]. Therefore, lots of researches on thermal dynamics and management of aircraft hydraulic system (AHS) have been carried out.

Parker and Mcquiston [5] published a research report which constructed a model of hydraulic pump, hydraulic motor, valve, dividing and combining device, as well as raised a power loss modeling method, calculation method of average oil temperature and calculation method of dynamic oil temperature. Engelhardt [6] developed a software package which could calculate the temperature of civil AHS. Levek and Performer [7] developed a software package by using thermal node modeling method. Li *et al*. [8] analyzed the characteristic of heat loads of AHS, and proposed some new considerations for thermal management system of AHS. Li and Jiao [9] established the dynamic thermal model of the piston pump considering

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housing leakage port, and clearly analyzed thermal mechanism. Dooley *et al.* [10] and Morioka *et al.* [11] analyzed several aircraft heat sinks and thermal management strategies, and pointed out that AHS should use fuel as main heat sink for its thermal management. German [12] proposed a general architecture towards overall thermal management strategies of airborne equipment and established thermal dynamic model of the fuel tank.

Previous researches are deficient in thorough investigations on thermal load prediction and thermal management mechanism within full mission profile. In order to make simulation, evaluation and improvement for current thermal management strategies of civil AHS, this paper carries out thermal dynamic modeling and the design of thermal management strategies within full mission profile. Firstly, according to energy conservation law, heat transfer and hydraulic fluid mechanics, this paper establishes general thermal dynamic equation of hydraulic components through thermal node and lumped parameter method. Secondly, the working and thermal mechanism of civil AHS, the thermal dynamic equations of key hydraulic subsystems such as hydraulic energy system, hydraulic actuating system, hydraulic oil tank, thermal management system are established by using the former general model. Thirdly, aimed at the thermal control and thermal management issues of civil AHS, the relative strategies are proposed. Finally, the main conclusions are summarized.

General thermal dynamic model of hydraulic control volume

Considering the control volume shown in fig. 1 and using lumped-parameter method, the equation which describes energy conservation law of control volume is:

$$\sum E_{\text{in}} - \sum E_{\text{out}} + \Delta Q_{\text{s}} + \Delta W_{\text{s}} = \Delta U_{\text{cv}} \tag{1}$$

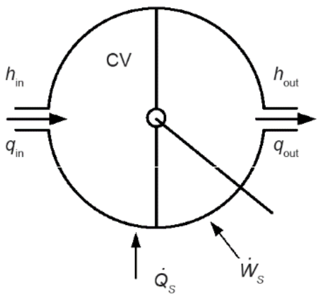

Figure 1. Control volume

where ΣE_{in} and ΣE_{out} are respectively influx and efflux of energy, ΔQ_{s} and ΔW_{s} – the heat increment, which transmits the outside, and the shaft work increment, which inputs the control volume from outside, respectively, $\Delta U_{\text{cv}} = c_p \Delta (m_{\text{cv}} T)$ – the increment of internal energy, c_p, m, and T – the specific heat capacity, mass and temperature of hydraulic oil of control volume, respectively.

Currently, the thermal dynamic simulation generally adopts the model in [13]:

$$\frac{\text{d}h}{\text{d}t} = \frac{1}{\rho V}\left[w_{\text{e}}(h_{\text{in}} - h_{\text{out}}) + \dot{Q}_{\text{s}} + \dot{W}_{\text{s}} + V\frac{\text{d}p}{\text{d}t} \right] \tag{2}$$

The issues of this model are inconvenient to be solved because of its pressure derivative term, and it does not reflect energy conversion and variable mass influence (*e. g.* immersed heat exchanger – HX in the fuel tank of AHS). In order to solve these problems, we must derive the new thermal dynamic equation. Firstly, substituting the internal energy change term in eq. (1) yields eq. (3):

$$c_p \frac{\text{d}(m_{\text{cv}}T)}{\text{d}t} = c_p m_{\text{cv}} \frac{\text{d}T}{\text{d}t} + c_p T \frac{\text{d}m_{\text{cv}}}{\text{d}t} = \sum \rho q_{\text{in}} h_{\text{in}} - \sum \rho q_{\text{out}} h_{\text{out}} + \dot{Q}_{\text{s}} + \dot{W}_{\text{s}} \tag{3}$$

On left of eq. (3), two terms to express change rate of internal energy have clear physical meaning for thermal analysis of hydraulic and fuel system, and they are related to the temperature change rate and the mass change rate of the control volume in hydraulic component, respectively. Compared with eq. (2), eq. (3) can describe energy-balance rule of hydraulic component more clearly and precisely.

Considering the fluid enthalpy $h = c_pT + (p/\rho)(1 - \alpha T)$, and rewrite eq. (3) yields:

$$c_p m_{\rm cv}\frac{{\rm d}T}{{\rm d}t} + c_p T\frac{{\rm d}m_{\rm cv}}{{\rm d}t} = \rho c_p\left(\sum q_{\rm in}T_{\rm in} - \sum q_{\rm out}T_{\rm out}\right) + \\ + (1-\alpha T)\left(\sum p_{\rm in}q_{\rm in} - \sum p_{\rm out}q_{\rm out}\right) + \dot{Q}_{\rm s} + \dot{W}_{\rm s} \tag{4}$$

During energy conversion and flow process inside hydraulic components, the definition of the power loss is $N_{\rm f}$, which is:

$$N_{\rm f} = \sum q_{\rm in}p_{\rm in}(1-\alpha T) - \sum q_{\rm out}p_{\rm out}(1-\alpha T) + \dot{W}_{\rm s} \tag{5}$$

Considering compressibility and thermal expansion of fluid and mass conservation law of the control volume, eqs. (6) and (7) can be written:

$$\dot{\rho} = \left(\frac{\rho}{\beta_e}\right)\dot{p} - \rho\alpha\dot{T} \tag{6}$$

$$\dot{m}_{\rm cv} = \rho\sum q_{\rm in} - \rho\sum q_{\rm out} = V\dot{\rho} + \rho\dot{V} \tag{7}$$

Substituting eqs. (5)-(7) into eq. (4), and neglecting the compressibility and thermal expansion of hydraulic oil, and the final thermal dynamic equation can be derived:

$$\rho c_p[V\dot{T} + T\sum q_{\rm in} - T\sum q_{\rm out}] = \sum \rho c_p q_{\rm in}T_{\rm in} - \sum \rho c_p q_{\rm out}T_{\rm out} + \dot{Q}_{\rm s} + N_{\rm f} \tag{8}$$

Equation (8) is more reasonable equation for the thermal analysis of hydraulic component. It opens up the coupling between hydraulic dynamics calculation and temperature dynamic calculation and clearly explains that the thermal load of hydraulic component is produced by the power loss $N_{\rm f}$ of the component. Power loss, heat exchange $\dot{Q}_{\rm s}$ on the control volume surface and mass flow change rate $\rho(\Sigma q_{\rm in} - \Sigma q_{\rm out}) = \dot{m}_{\rm cv}$ determine thermal dynamics of hydraulic component.

Thermal dynamic modeling for civil aircraft hydraulic system

The scheme of thermal dynamic modeling

During the process of full mission profile, civil AHS can inevitably produce the heat load, in order to quickly and accurately compute the temperature change and effectively conduct thermal management, it is very necessary to establish thermal dynamic model aimed at key hydraulic components based on full mission profile. Considering the heat load characteristics of the civil AHS, the functional subsystem modeling based on the general thermal dynamic model in section *Geneal thermal dynamic model of hydraulic control volume* is proposed, it is shown in fig. 2. This modeling scheme divides the hydraulic system into four parts: hydraulic energy system, hydraulic actuating system, hydraulic oil tank and thermal management system. Obviously, it can clearly analyze thermal dynamics and conduct thermal management.

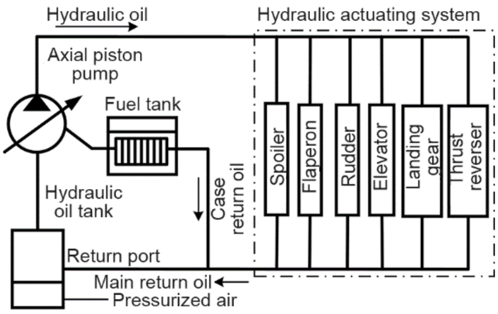

Figure 2. The modeling scheme diagram

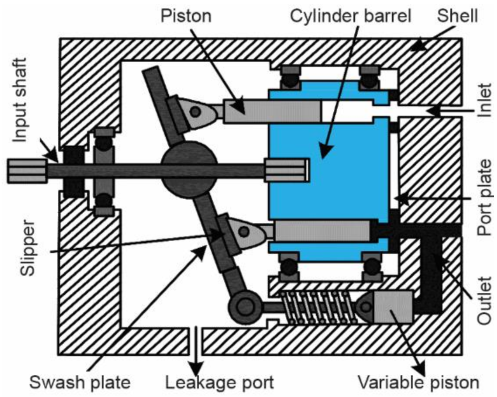

Figure 3. Schematic diagram of aircraft axial piston pump

Thermal dynamic modeling of hydraulic energy supply system

Generally, AHS widely adopts the constant pressure variable displacement axial piston pump (engine or electric motor driven, EDP or MDP) with case drain, it is shown in fig. 3, and a HX is settled in the drain line for releasing the heat of the case drain oil.

Divided the pump with case drain into case drain chamber and working chamber, and based on eq. (8), the thermal dynamic equations of two control volumes can be derived:

$$\rho c_p (q_{pi} T_{pi} - q_{po} T_{po}) + N_{fp} - (1-\eta_v) q_{pt} \cdot$$
$$\cdot (p_{po} + \rho c_p T_{po}) - \dot{Q}_{pc} = c_p m_{cvp} \dot{T}_{po} \quad (9)$$

$$\dot{Q}_{pc} - h_{ce} A_{ce} (T_{pc} - T_{pe}) + (1-\eta_v) q_{pt} \cdot$$
$$\cdot [c_p \rho (T_{po} - T_{pc}) + p_{po} - p_{pc}] = c_p m_{cvc} \dot{T}_{pc} \quad (10)$$

where $\dot{Q}_{pc} = h_{pc} A_{pc} (T_{po} - T_{pc})$, h_{pc}, and A_{pc} are the equivalent convective heat-transfer flow rate, heat-transfer coefficient, and heat-exchange area and from pump working chamber to case chamber, respectively, h_{ce} and A_{ce} are the convective heat-transfer coefficient and heat exchange area from pump case chamber to the environment, subscripts p, c, i, and o denotes the pump, case drain, inlet, and outlet, respectively, p_{pi}, p_{po}, q_{pi}, and q_{po} denote the pressure and flow rate of the pump at inlet and outlet, the T_{pi}, T_{pc}, T_{po}, and T_{pe} denote the temperature of the pump in inlet, case drain port, outlet and surrounding, respectively, and N_{fp} is the power loss of the pump. The formula of N_{fp} is:

$$N_{fp} = (1-\eta_m \eta_v) N_{in} = (1-\eta_m \eta_v) \Delta p_{pt} q_{pt}, \quad \Delta p_{pt} \eta_m = p_{po} - p_{pi} \quad (11)$$

where N_{in}, η_m, η_v, Δp_{pt}, and q_{pt} are the input power, mechanical efficiency, volumetric efficiency, theoretical pressure difference between outlet and inlet, and theoretical flow rate of the pump, respectively, and $\Delta p_{pt} \eta_m = p_{po} - p_{pi} = \Delta p$. The η_m and η_v are the function of non-dimension ratios $\mu\omega/\Delta p$ and D_p/D_{pmax}, μ, ω, and D_p, are the dynamic viscosity of the oil, and angular speed and the displacement of the pump, respectively. The values of η_m and η_v can be obtained from catalogue of pump or calculated from the mechanical and leakage power losses.

Thermal dynamic modeling of hydraulic actuating system

In a given mission profile, the pressurized oil outputs from the outlet of piston pump to hydraulic actuating system including actuators of primary control surfaces and auxiliary manipulating surfaces, gears, steering, brake, and engine reverse thrust control mechanism, and then returns to the oil reservoir after merging the main returning oil tube and the hydraulic oil flowed out from the outlet of HX. In order to simplify the complexity of the modeling, power loss and heat transfer flow rate of supplying and returning tubes are considered by merging to the relative terms in the actuating system. Considering most of components among hydraulic actuating system are located inside airborne equipment bay, its heat can be partly dissipated through the surrounding air. Based on eq. (8), its thermal dynamic equation can be written:

$$\rho c_p (q_{\text{po}} T_{\text{po}} - q_{\text{ao}} T_{\text{ao}}) + N_{\text{fa}} - \dot{Q}_{\text{ac}} = c_p m_{\text{cva}} \dot{T}_{\text{ao}} \tag{12}$$

where m_{ha}, N_{fa}, q_{ao}, and T_{ao} are the equivalent mass, the power loss, returning flow rate, and temperature of the actuating system, respectively, Q_{ac} is the equivalent heat transfer between hydraulic actuating system and its surrounding air, $Q_{\text{ac}} = h_{\text{ac}} A_{\text{ac}} (T_{\text{ao}} - T_{\text{ae}})$.

Thermal dynamic modeling of hydraulic oil tank

Hydraulic oil tank is responsible for oil storage, sediment contaminated particles and heat-dissipation. The inputs of the tank are the output of the HX and the output is the actuating system which contains mail return oil tube, and its output is the inlet of the pump. According to eq. (8), its thermal dynamic equation can be expressed:

$$c_p m_{\text{te}} \dot{T}_{\text{to}} = c_p \rho [(q_{xo} T_{xo} + q_{ao} T_{ao} - (q_{xo} + q_{ao}) T_{\text{to}}] - K_{te} A_{te} (T_{\text{to}} - T_{\text{e}}) \tag{13}$$

where m_{te} and T_{to} are the equivalent mass and temperature of the hydraulic oil in the tank, T_{e} – the surrounding temperature, K_{te} and A_{te} – the equivalent convective heat-transfer coefficient and heat exchanging area of the tank.

Thermal dynamic modeling of thermal management system

For hydraulic system of civil aircraft, thermal management commonly uses the HX settled in the case drain pipeline, and the heat sinks generally adopts fuel oil or ram air. The preferred heat sink, fuel, meantime it also absorbs the heat loads from lubrication and cooling system of the generator and transfer box, environment system, electronic equipment in aircraft. For large passenger aircraft, more than 20 tons of fuel is carried on takeoff, the fuel has the powerful heat load absorbing ability and minimum cost loss of heat control because the heated fuel will be directly burned in the engine combustor as long as it is below the coking temperature. The types of HX in the AHS have immersed hydraulic oil/fuel HX, forced convection hydraulic oil/fuel HX, hydraulic oil/ram air HX, and compound HX (used in Airbus 380), and currently most of hydraulic system in aircraft adopts the first two HX. Herein, the establishment of thermal dynamic model of immersed hydraulic oil/fuel HX is discussed as an example, the cold side of this kind of HX is immersed in the primary fuel tank. Based on eq. (8), its heat dynamic equation can be written:

$$c_p \rho q_{\text{cr}} T_{\text{hxi}} - c_p \rho q_{\text{cr}} T_{\text{hxo}} - K_{\text{hx}} A_{\text{hx}} \Delta \overline{T}_{\text{hx,ln}} = c_p m_{\text{hx}} \dot{T}_{\text{hxo}} \tag{14}$$

$$K_{\text{hx}} A_{\text{hx}} \Delta \overline{T}_{\text{hx,ln}} - \dot{Q}_{\text{fte}} = c_{pf} m_{\text{ft}} \dot{T}_{\text{ft}} \tag{15}$$

where K_{hx}, A_{hx}, T_{hxi}, and T_{hxo} are the equivalent convective heat-transfer coefficient, heat exchange area of immersed hydraulic oil/fuel HX, $\Delta \overline{T}_{\text{hx,ln}}$ is the log mean temperature difference, $\Delta \overline{T}_{\text{hx,d}} = (T_{\text{hxi}} - T_{\text{hxo}}) / \ln[(T_{\text{hxi}} - T_{\text{ft}})/(T_{\text{hxo}} - T_{\text{ft}})]$, T_{ft} and m_{ft} are the temperature and the equivalent mass of the fuel in the fuel tank, Q_{fte} is the equivalent transfer heat flow rate between the fuel and the surrounding, and c_{pf} is the equivalent specific heat capacity in the fuel tank. With the increase of flight time, the m_{ft} gradually decreases, and its computation formula is:

$$m_{\rm ft} = m_{\rm ft0} - \int_0^t \dot{m}_{\rm fuel} {\rm d}t \tag{16}$$

where m_{ft0} is the initial mass of the fuel, and $\dot{m}_{fuel}$ – the fuel consumption rate of the aero-engine. Defining the HX characteristic coefficient of the fuel tank $a_{hx} = K_{hx}A_{hx}/(\rho q_{cr}c_p)$ in eq. (14), and $a_{hx} > 10$ is expected. The larger a_{hx} means the better heat exchange performance. For example, the value a_{hx} of the HX in a hydraulic system of B737 is about 16.0-24.0. Considering the response speed of T_{hxo} is much faster than that of T_{ft}, and thus eq. (14) can be simplified:

$$c_p \rho q_{\rm cr} T_{\rm hxi} - c_p \rho q_{\rm cr} T_{\rm hxo} - K_{\rm hx} A_{\rm hx} \Delta \overline{T}_{\rm hx,ln} = 0 \tag{17}$$

Using the successive over-relaxation method for non-linear eq. (17) solves T_{hx} at the k-time iteration step:

$$T_{{\rm hxo},k}(i+1) = \omega \left[-a_{\rm hx} \frac{T_{{\rm hxi},k} - T_{{\rm hxo},k}(i)}{\ln \dfrac{T_{{\rm hxi},k} - T_{{\rm ft},k}}{T_{{\rm hxo},k}(i) - T_{{\rm ft},k}}} + T_{{\rm hxi},k} \right] + (1-\omega) T_{{\rm hxo},k}(i) \tag{18}$$

where $\omega \le 1$ is a modification factor to enhance convergence in limited iterations.

Thermal dynamic modeling of AHS

The dynamic model of the overall AHS can be obtained after combining the dynamic equations of the aforementioned four parts dynamic model, and the thermal dynamic variation process can be calculated. The dynamic simulation needs to be conducted by separating different stages during a flight mission profile, and the pressure, flow rate, and power loss of each subsystem should be determined in advance.

Thermal management strategies towards civil AHS

The thermal dynamic control system of civil AHS

Thermal dynamic control and management system is a very important part in the civil AHS, and it is responsible for controlling the temperature of hydraulic system in the allowable range. During the process of carrying out a given mission, various power losses which are produced by throttling loss, oil leakage loss and viscous friction loss finally result in the oil temperature-rise. Hydraulic oil which carries lots of heat will make the further increase of the leakage loss, thermal expansion jam and aging of sealing components. Long time temperature-rise might even cause safety accidents. Additionally, excessively low oil temperature can also make hydraulic system not start. In order to control the temperature of hydraulic oil and ensure not too high fuel temperature, most of civil AHS usually adopt HX immersed inside fuel tank to absorb the heat load. The heat transfer process of the HX is natural convection which mainly depends on fuel temperature, thermal control is realized by temperature-enabled solenoid valve, and its schematic diagram is shown in fig. 4.

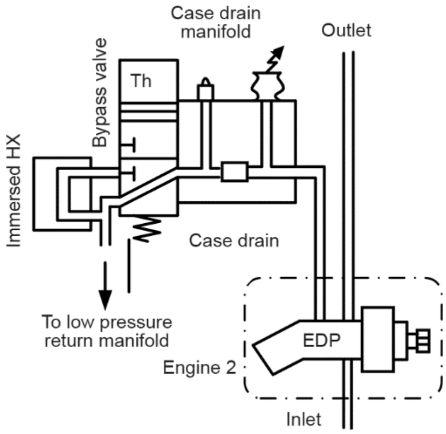

Figure 4. Thermal management of A350 AHS; EDP – electric driven pump

New type of thermal management strategies

Considering that civil aircraft usually flies at subsonic speeds, and has interior loose layout and less maneuvering flights, so the heat-generation issue of airborne equipment is not more serious than fighter, but the thermal load of AHS with 35 MPa pressure (*e. g.* B787, A380, A350) is larger than that of AHS with 21 MPa pressure, large thermal load commonly takes place in taking-off, landing, and flight bump compensation stages. Because only parts of heat loads are dissipated through very long tubing, thus the heat control during these stages is still very necessary. Currently, Boeing, and Airbus Company mainly utilize fuel as heat sink to conduct thermal management of civil AHS. The B737, B777, and A350 adopt the strategy which sets up HX immersed inside fuel tank to manage heat load in case drain of the piston pump, the other heat is mainly managed through hydraulic oil tank and very long tube. The A320 in Airbus Company and C919 in China adopt the strategy which mainly utilizes hydraulic oil tank and tubing which passes through fuel tank to manage its heat. On the basis of former thermal management strategy of Boeing aircraft, B787 also uses dual-stage rotational speeds MDP and dual-stage pressures EDP to make its hydraulic system switch to low-power mode during the cruise flight, thus partly alleviates heat-generation and temperature-rise issue due to low efficiency of the pump and throttling loss of the valve. Moreover, A380 aircraft made by Airbus Company adopts almost completely new strategy and a compound HX, it is shown in in fig. 5, which can choose ram air as first heat sink and fuel as the second heat sink, each AHS is equipped with hydraulic oil/ram air HX and forced convection hydraulic oil/fuel HX, and the former is equipped with cooling fan driven by hydraulic motor to en-

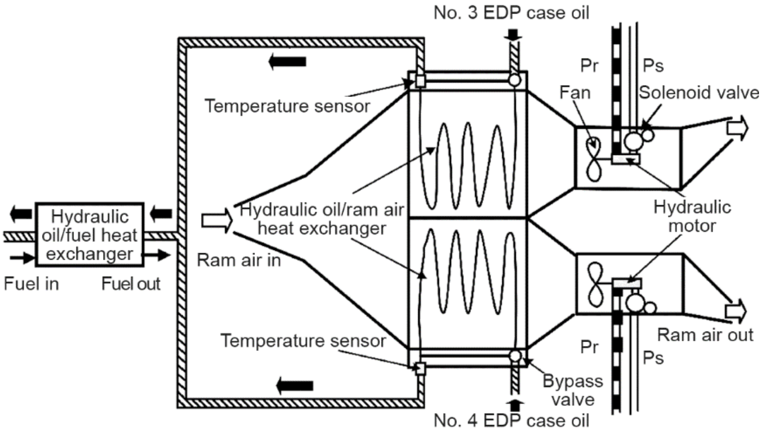

Figure 5. Thermal management system in a hydraulic system of A380 civil aircraft

sure the sufficient cooling efficiency when the aircraft is in ground or low-speed flight. Commonly, AHS uses hydraulic oil/ram air HX for thermal control; and when the temperature of hydraulic oil can be not controlled below its upper limit, forced convection HX will absorb the extra thermal loads. The thermal management system schematic diagram in a hydraulic system of A380 civil aircraft is shown in fig. 5.

Conclusion

Aimed at the demand of thermal dynamic prediction and thermal management of the AHS, this paper proposed thermal dynamic model of universal hydraulic component by using theoretical analysis, and established the equations of main function systems. The presented computation method of heat loads and thermal control strategies can exactly describe the characteristics of AHS and direct the design of thermal management system. The next work of this paper is to conduct the numerical simulation and principle experiment for the practical AHS.

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