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Thermal-hydraulic Modeling and Simulation of the Hydraulic System Based on the Electro-Hydrostatic Actuator

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Abstract

Electro-hydrostatic actuator (EHA) was a typical power-by-wire (PBW) actuator, which was widely-used in large commercial aircrafts, such as Airbus A380. The electro-hydrostatic actuator(EHA) had the advantages of small sizes, light weight, high power density, high reliability and maintainability. With the application of EHA in large commercial airplanes, the airworthiness certification of EHA became an new problem. The precondition of the airworthiness certification of EHA was to understand its operating principle and characteristic. Because of no centralized hydraulic oil tank and short cycle oil circuit, the temperature-rise of the hydraulic system in EHA always kept high during operation. Therefore, it was important to build the thermal-hydraulic models of the hydraulic system in EHA, and to do the thermal analysis of the EHA by this model. In this paper, a lumped-parameter thermal-hydraulic model of the hydraulic part in EHA was proposed. The model was built based on the detailed analysis of the heat transfer of the hydraulic part in EHA. By the simulation of a practical system and the comparison with the traditional hydraulic system, the accuracy and practicality of this model was verified.

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Keywords: thermal-hydraulic; electro-hydrostatic actuator; temperaure-rise; thermal modeling

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1. Introduction

With representative of the Power-By-Wire (PBW), the electro-hydrostatic actuator (EHA) was replacing the conventional hydraulic actuator in the large commercial airplanes, such as Airbus A380 and Boeing 787. Compared with the hydraulic actuator, EHA took electric energy as the power transfer mode. By this new power transfer mode, EHA did not need the centralized hydraulic oil tank and the oil pipes over the airplane. Therefore, the EHA could reduce the weight of airplane and eliminate the noise and

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vibration caused by oil pipes[1, 2]. Furthermore, the EHA could raise the reliability and improve maintainability of airplane.

EHA was a new technology. Any new technology must take the airworthiness certification before applied in civil airplanes. The precondition of the airworthiness certification of EHA was to understand its operating principle and characteristic. Because the EHA did not contain the entralized hydraulic oil tank and the circulating circuit of hydraulic oil was short, there was not enough heat radiating area for the hydraulic oil, and the EHA was under an insufficient cooling states, the temperature-rise of the components and hydraulic oil of EHA was significant different from the hydraulic actuator. In operation, the temperature-rise of the hydraulic oil in the EHA was high. Significant temperature-rise of hydraulic oil could degrade performance, as well as caused irreparable and irreversible failures to those thermal sensitive components of EHA[3]. Therefore, it was important to build the thermal-hydraulic models of the hydraulic system in EHA, and implement the thermal analysis in the design process.

Currently there are two main methods to build thermal-hydraulic models of hydraulic systems: the modeling software and the lumped-parameter method. There were lots of mature softwares for thermal-hydraulic modeling of hydraulic systems. In [4], a thermal-hydraulic model of double press axial piston pump was established in AMESim, and a thermal analysis was made to compare the temperature-rise between the double press axial piston pump and constant pressure axial piston pump. In [5], the thermal-hydraulic modular modeling and simulation was implemented by Dymola. In [6, 7], heat generation in EHA was analysed by HOPSAN. The another method to build thermal-hydraulic models of hydraulic systems was by lumped-parameter method[8]. The lumped-parameter method had been widely applied to build thermal-hydraulic models of hydraulic components, such as accumulators[9], hydraulic motors[10] and piston pumps[11,12]. The characteristic of the two methods could be summarized as below:

- The modeling software was suitable to build the thermal-hydraulic models of standard hydraulic components. It had obvious advantages on simplicity and timesaving. However, it was not suitable to build the models of special hydraulic components or systems
- The lumped-parameter method required more complicated modeling process and longer calculation time, however, it was more flexible to build the models of special hydraulic components

Both methods had their own applicable situation. Considering the particularity of EHA in structure and operation principle, the lumped-parameter method is more suitable to build the thermal-hydraulic model of EHA.

This paper presents a novel thermal-hydraulic model of the hydraulic system in EHA. Based on the detailed analysis of the heat transfer of the hydraulic system in EHA, the model was built by the lumped-parameter method. By the simulation of a practical system and the comparison with the traditional hydraulic system, the accuracy and practicality of this model was verified.

2. The lumped-parameter method for the thermal-hydraulic modeling of the hydraulic system

The thermal-hydraulic model of the hydraulic system in EHA is built by the lumped-parameter method. The heat conservation equation is the basic equation for thermal-hydraulic modeling by lumped-parameter method. The basic relationship for the thermal exchange of the fluid over a hydraulic system is the first law of thermodynamics applied to a flow process of the control volume[13]. The control volume is shown in Fig 1.

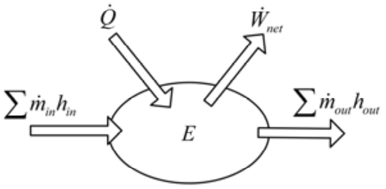

Fig. 1. control volume

The relationship of the energy conservation in the control volume could be gotten by the first law of thermodynamics, which was expressed as below:

$$\dot{Q}-\dot{W}_{net}=\sum \dot{m}_{out}h_{out}-\sum \dot{m}_{in}h_{in}+\dot{E} \tag{1}$$

In Eq. (1), the heat exchange in the control volume is represented as $\dot{Q}$, and $\dot{W}_{net}$ is the rate of the net work by the control volume, E represented the sum of the internal energy of the control volume. $\dot{m}_{in}$ represented the rate of the mass flowing into the control volume, $\dot{m}_{out}$ is the rate of the mass flowing out of the control volume, h_{in} represented the specific entropy of the mass flowing into the control volume, h_{out} represented the specific entropy of the mass flowing out of the control volume.

According to [8], let T be the temperature of the control volume, based on Eq. (1), T change with time could be expressed as below:

$$\frac{dT}{dt}=\frac{1}{c_p m}[\sum \dot{m}_{in}(c_p(T_{in}-T)+(1-\alpha_p T)v(p_{in}-p))-\dot{Q}-\dot{W}_{net}+mT\alpha_p v\frac{dp}{dt}] \tag{2}$$

where: c_p represented the specific heat of the control volume at constant pressure, m represented the mass of the control volume, T_m represented the temperature of the mass flowing into the control volume, α_p represented volume expansion coefficient of the control volume, v represented the specific volume of the control volume, p_{in} represented the pressure of the mass flowing into the control volume, p represented the pressure of the control volume.

The hydraulic system could be divided into several control volumes by temperature distribution. The temperature change with time of these control volumes can be expressed by Eq. (2). All the expressions constitute the equations. The temperature of the control volumes could be gotten by solving the equations.

3. Heat transfer analysis of the hydraulic system in EHA

A detailed heat transfer analysis of the hydraulic system in EHA was made on the below, which is the base of thermal-hydraulic modeling.

3.1. The structure and operation principle of the EHA

The typical structure of the EHA was shown in Fig 2, which was composed of the hydraulic cylinder, the servo motor, the piston pump and the accumulator. The speed of hydraulic actuator system was controlled by the flow. In EHA system, the piston pump was driven by the servo motor. Therefore, the change of the servo motor speed could be used to adjust the flow of the pump. The accumulator and two check valves were used to keep the minimum pressure of the system and avoid the cavitation. The EHA system was protected by the bypass valve and two relief valves. The differences between the EHA and hydraulic actuator can be summarized as below:

- By the application of power-by-wire, there is no centralized hydraulic oil tank in EHA.
- The hydraulic oil just needs to circulate around the internal components of EHA.
- According to the limits of size and weight, the heat radiating area of the EHA is small for the hydraulic oil.

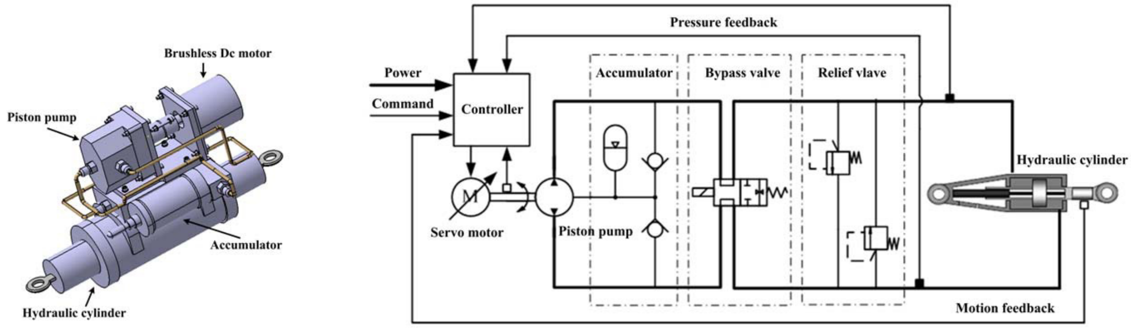

Fig. 2. (a) EHA; (b) operation principle drawings of EHA

3.2. The heat transfer analysis of the hydraulic system in EHA

The heat generation of the hydraulic system is mainly because the power losses of the hydraulic components in EHA. The heat is transferred by hydraulic oil among these components. Meanwhile, the heat is exchanged between the hydraulic pipes and the external environment or between the shells of these components and the external environment.

The heat transferred among the hydraulic components mainly depend on the hydraulic oil. Therefore, it is important to analyze the circulation of the hydraulic oil in the EHA. The circulation of the hydraulic oil is shown in Fig 3.

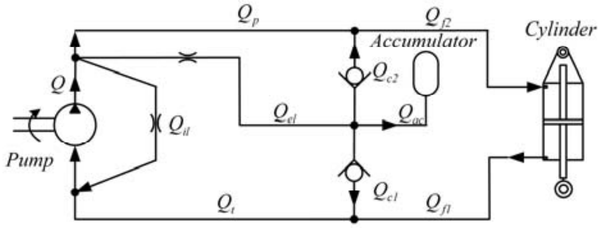

Fig. 3. circulation of the hydraulic oil in EHA

In Fig 3, the arrows indicates the flow direction of the hydraulic oil, the symbols upon the lines represent the quantity of flow. Q is the total quantity of the piston pump, Q_{il} is the quantity of the internal leakage of the piston pump, Q_{el} is the quantity of the external leakage of the piston pump, Q_p is the quantity of the discharging oil of the piston pump, Q_t is the quantity of the absorbing oil of the piston pump, Q_{ac} is the quantity of the accumulator, Q_{c1} and Q_{c2} is the quantity of the check valve, Q_{f1} and Q_{f2} is the quantity of the hydraulic cylinder.

Accroding to the analysis of the circulation of the hydraulic oil in EHA, the heat transfer of the hydraulic system in EHA can be shown in Fig 4.

In Fig 4, the different color represents the hydraulic oil in the different temperature. T_t is the temperature of the hydraulic oil in the suction chamber of the piston pump, T_p is the temperature of the hydraulic oil in the expulsion chamber of the piston pump, T_l is the temperature of the leakage hydraulic oil in piston pump, T_{ac} is the temperature of the hydraulic oil in the accumulator, T_c is the temperature of the hydraulic oil in the hydraulic cylinder. The color lines represent the flow of the hydraulic oil. The black in Fig 2 represents the shells of the hydraulic components. T_{wp} is the temperature of the piston pump shell, T_{wa} is the temperature of the accumulator shell, T_{wc} is the temperature of the hydraulic cylinder shell. The black dashed lines represent the heat exchange between the shells and external environment.

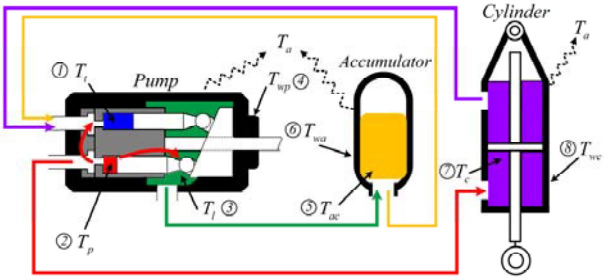

Fig. 4. the heat transfer of the hydraulic system in EHA

4. Thermal-hydraulic model of the hydraulic system in EHA

According to the heat transfer analysis, the hydraulic system in EHA is divided into eight parts by different temperature. Based on the above theory, each part can be treated as a control volume, which is called a node. The eight nodes thermal-hydraulic model of the hydraulic system in EHA is shown in Fig 5.

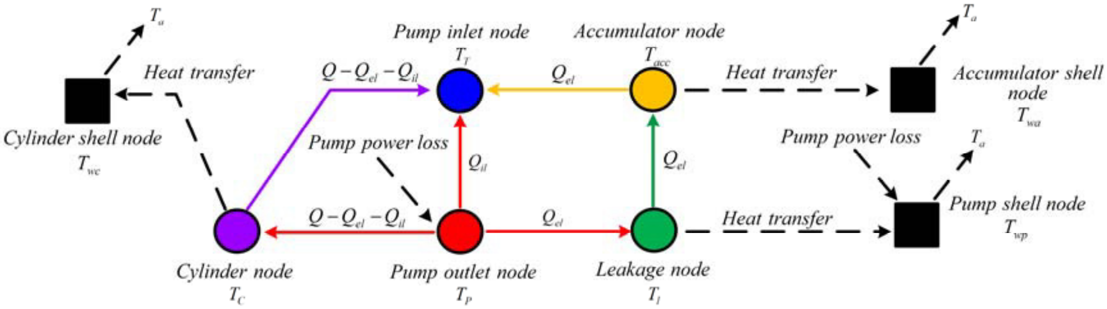

Fig. 5. thermal-hydraulic model of the hydraulic system in EHA

In Fig 5, the circles represent the hydraulic oil nodes. The blue circle represents the pump inlet node, the red circle represents the pump outlet node, the green circle represents the pump leakage node, the purple circle represents the cylinder node, the yellow circle represents the accumulator node. The color lines shows the transfer direction of the hydraulic oil, and the color of the lines is same with the color of the hydraulic oil node. The black squares represent the shells of the hydraulic components. The dashed lines represent the heat exchange between the shells and external environment.

According to Eq. (2), the heat balance equations of the eight nodes can be expressed as below:

- The pump inlet node:

$$\begin{aligned}\frac{dT_t}{dt}=\frac{1}{c_P m_t}[&\rho(Q-Q_{el}-Q_{il})(c_p(T_C-T_T)+(1-\alpha_P\frac{(T_C+T_t)}{2})v(P_C-P_T))+\rho Q_{il}(c_p(T_P-T_t)+(1-\alpha_P\frac{(T_P+T_t)}{2})v(P_P-P_T))\\&+\rho Q_{el}(c_p(T_{ac}-T_t)+(1-\alpha_P\frac{(T_{ac}+T_t)}{2})v(P_{ac}-P_T))+\rho(Q-Q_{el}-Q_{il})c_p(T_C-T_t)+\rho Q_{il}c_p(T_P-T_t)+\rho Q_{el}c_p(T_{ac}-T_t)+T_t\alpha_P V_t\frac{dP_T}{dt}]\end{aligned} \tag{3}$$

- The pump outlet node:

$$\frac{dT_P}{dt}=\frac{1}{c_P m_P}[\rho(Q-Q_{il})(c_P(T_t-T_P)+(1-\alpha_P\frac{(T_p+T_t)}{2})v(P_T-P_P))+Q(P_P-P_T)+L_n+L_d+T_P\alpha_P V_P\frac{dP_p}{dt}] \tag{4}$$

- The pump leakage node:

$$\frac{dT_l}{dt}=\frac{1}{c_P m_l}[\rho Q_{el}(c_p(T_P-T_l)+(1-\alpha_p\frac{(T_P+T_l)}{2})v(P_P-P_l))-k_{fw}A_{fwp}(T_l-T_w)+T_l\alpha_P V_l\frac{dP_l}{dt}] \tag{5}$$

- The pump shell node:

$$\frac{dT_{wp}}{dt}=\frac{1}{c_{wp}m_{wp}}[k_{fwp}A_{fwp}(T_l-T_{wp})-k_{wpa}A_{wpa}(T_{wp}-T_a)+L_c] \tag{6}$$

- The accumulator node:

$$\frac{dT_{acc}}{dt}=\frac{1}{c_P m_{acc}}[\rho Q_{el}(c_p(T_l-T_{acc})+(1-\alpha_P\frac{(T_l+T_{acc})}{2})v(P_l-P_{acc}))+\rho Q_{el}c_p(T_l-T_{acc})+T_{acc}\alpha_P V_{acc}\frac{dP_{acc}}{dt}] \tag{7}$$

- The accumulator shell node:

$$\frac{dT_{wp}}{dt}=\frac{1}{c_{wp}m_{wp}}[k_{fwp}A_{fwp}(T_l-T_{wp})-k_{wpa}A_{wpa}(T_{wp}-T_a)+L_c] \tag{8}$$

- The cylinder node:

$$\frac{dT_{acc}}{dt}=\frac{1}{c_P m_{acc}}[\rho Q_{el}(c_p(T_l-T_{acc})+(1-\alpha_P\frac{(T_l+T_{acc})}{2})v(P_l-P_{acc}))+\rho Q_{el}c_p(T_l-T_{acc})+T_{acc}\alpha_P V_{acc}\frac{dP_{acc}}{dt}] \tag{9}$$

- The cylinder shell node:

$$\frac{dT_{wc}}{dt}=\frac{1}{c_{wc}m_{wc}}[k_{fwc}A_{fwc}(T_c-T_{wc})-k_{wca}A_{wca}(T_{wc}-T_a)] \tag{10}$$

where: c_p , c_{wp} , c_{wa} , c_{wc} is the specific heat of the hydraulic oil, the piston pump shell, the accumulator shell and the cylinder shell at constant pressure. V_t , V_p , V_l , V_{acc} , V_c is the volume of the hydraulic oil in the pump inlet node, the pump outlet node, the pump leakage node, the accumulator node and the cylinder node. m_t , m_p , m_l , m_{wp} , m_{acc} , m_{wa} , m_c , m_{wc} is the mass of the pump inlet node, the pump outlet node, the pump leakage node, the pump shell node, the accumulator node, the accumulator shell node, the cylinder node and the cylinder shell node. A_{fwp} is the radiation area between the piston pump shell and the hydraulic oil, A_{wpa} is the radiation area between the piston pump shell and the external environment, A_{fwa} is the radiation area between the accumulator shell and the hydraulic oil, A_{waa} is the radiation area between the accumulator shell and the external environment, A_{fwc} is the radiation area between the cylinder shell and the hydraulic oil, A_{wca} is the radiation area between the cylinder shell and the external environment. k_{fwp} , k_{wpa} , k_{fwa} , k_{waa} , k_{fwc} , k_{wca} are the convective heat transfer coefficients of the radiation between the hydraulic components and hydraulic oil, and between the hydraulic components and the external environment[20]. l_n , l_d , l_u are the power losses of the pump by the viscous friction, hydraulic oil flow and dry friction.

5. Simulation and comparision

In order to verity the the accuracy and practicality of this model, a simulation of a practical hydraulic system in EHA is made in this section. In Eq. (3) to Eq. (10), the quantity of the pump piston is needed. The total quantity of the piston Q can be calculated as below:

$$Q = D \cdot \omega \tag{11}$$

where: D is the displacement of the piston pump, ω is the rotational speed of the servo motor.

The quantity of the internal leakage of the piston pump Q_{il} and the quantity of the external leakage of the piston pump Q_{el} can be calculated by the volumetric efficiency η_v , which is shown as below:

$$\begin{cases} Q_{el} = 0.8 \cdot Q \cdot (1-\eta_v) \\ Q_{il} = 0.2 \cdot Q \cdot (1-\eta_v) \end{cases} \tag{12}$$

The parameters of the EHA can be found in Appendix A. The result of the simulation is shown in Fig 6.

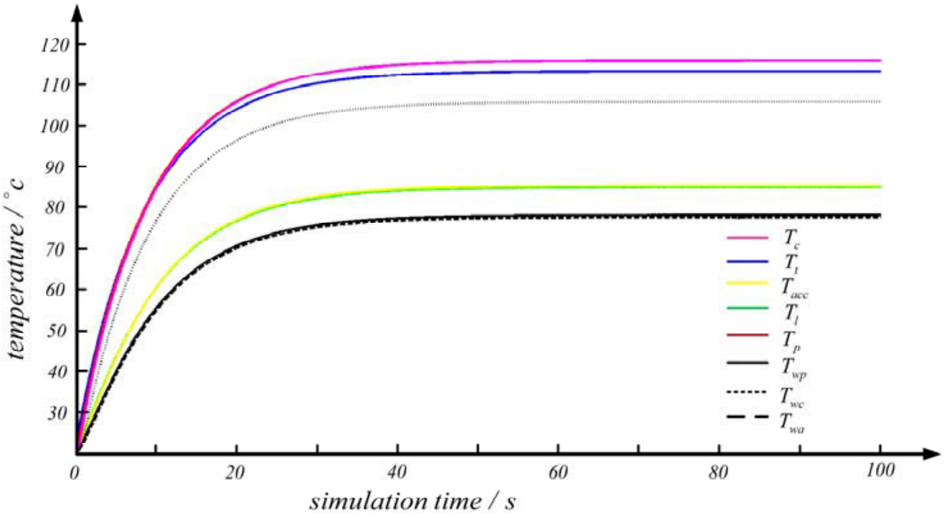

Fig. 6. simulation result of the thermal-hydraulic model of the hydraulic system in EHA

Several points could be seen from Fig 6 as following:

- Among the hydraulic oil nodes, the pump outlet node has the highest temperature, which is 117 c°. The temperature of the cylinder node is close to the temperature of the pump outlet node, this is because the hydraulic oil pipes are short in EHA, the heat transferred between the pipes and the external environment is very little.
- Among the shell nodes, the cylinder shell node has the highest temperature, which is 105 c°. The temperature of the shell nodes are closely related to the radiating area of these hydraulic components.
- The temperature of the accumulator node is much lower than the temperature of the pump outlet node, this reflects the accumulator in EHA has the same function as the oil tank in typical hydraulic system.

Indicated by Fig 6, Both the temperature of the pump inlet node and outlet node is much higher than the temperature of others. This is a special characteristic of the hydraulic system in EHA. For comparision, a thermal-hydraulic model of a piston pump in the typical hydraulic system is built and simulated with the same parameters of the piston pump in EHA. The thermal-hydraulic model of the piston pump in the typical hydraulic system is shown in Fig 7, which is also built by the lumped-parameter method.

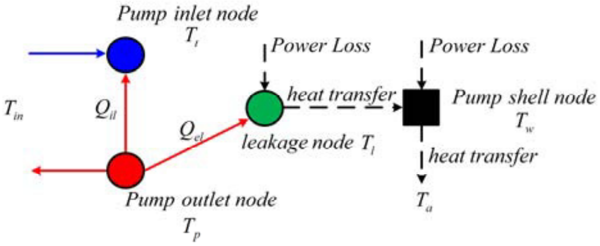

Fig. 7. thermal-hydraulic model of the piston pump in the typical hydraulic system

In the typical hydraulic, the hydraulic oil is absorbed from the oil tank. Because the radiating area of the oil tank is big enougth, the temperature of the inlet oil could be as a constant T_{in}. The heat balance equations of the nodes can be expressed as below:

$$\begin{cases} \dfrac{dT_t}{dt} = \dfrac{1}{c_P m_t}[\rho Q_{pt}(c_p(T_p - T_t) + (1-\alpha_P \dfrac{(T_p + T_t)}{2})v(P_P - P_T) + \rho D\omega c_p(T_{in} - T_t) + T_t\alpha_P V_T \dfrac{dP_T}{dt}] \\ \dfrac{dT_P}{dt} = \dfrac{1}{c_P m_P}[\rho\omega D(c_P(T_t - T_P) + (1-\alpha_P \dfrac{(T_p + T_t)}{2})v(P_T - P_P)) + D\omega(P_P - P_T) + L_n + L_d + T_P\alpha_P V_P \dfrac{dP_p}{dt}] \\ \dfrac{dT_l}{dt} = \dfrac{1}{c_P m_l}[\rho Q_{pl}(c_p(T_P - T_l) + (1-\alpha_p \dfrac{(T_P + T_l)}{2})v(P_P - P_l)) - k_{fw}A_{fw}(T_l - T_w) + T_l\alpha_P V_l \dfrac{dP_l}{dt}] \\ \dfrac{dT_w}{dt} = \dfrac{1}{c_w m_w}[k_{fw}A_{fw}(T_l - T_w) - k_{wa}A_{wa}(T_w - T_a) + L_c] \end{cases} \quad (13)$$

The result of the simulation is shown in Fig 8.

By comparing Fig 8 with Fig 6, the temperature of the nodes in EHA is much higher than the one in the typical hyraulic system, this is because the EHA is an insufficient cooling hydraulic system. The temperature of the pump outlet node in both systems is highest, however, the temperature of the inlet node in EHA is much higher than the one in the typical hydraulic system. The reason is that there is an oil tank in the typical hydraulic system, which provides enough radiating area to the hydraulic oil. Therefore, the temperature of the pump inlet node in the typical hydraulic system is close to the temperature of the hydraulic oil in the tank. Moreover, the rising time of the temperature in EHA is much shorter than the one in the typical hydraulic system.

By the simulation and the comparision, the accuracy and practicality of this model proposed in this paper is verified. The thermal characteristics of the hydraulic system in EHA can be reflected by this model.

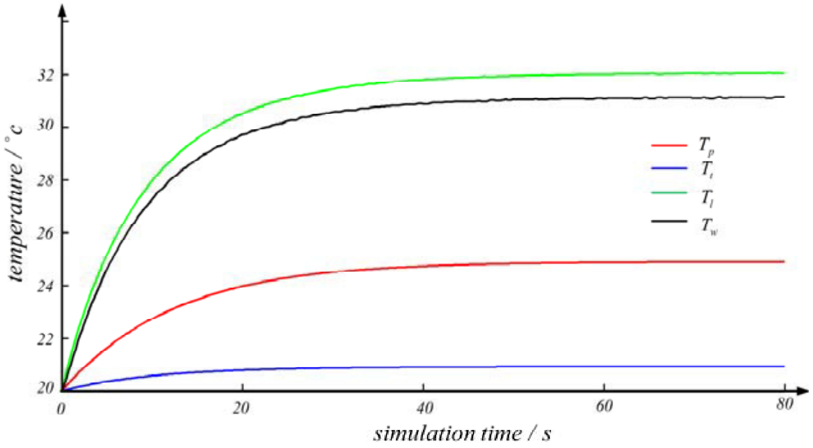

Fig. 8. simulation result of the thermal-hydraulic model of the piston pump in the typical hydraulic system

6. Conclusion

In this paper, a detailed heat analysis of the hydrulic system in EHA was made, and a thermal-hydraulic model was built by the lumped-parameter method. This novel model has the features as following:

- The model implements the heat analysis of the hydraulic system in EHA by the lumped-parameter method
- Compared with the model built by FEA or CFD, this model has the advantage of timesaving and easy building
- By the simulation and the comparision, the accuracy and practicality of this model was verified. Therefore, the thermal characterics of the hydraulic system in EHA can be reflected by this model.

According to the above features, this novel model could be applied for the design and airworthiness certification of EHA.

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Appendix A. The key parameters of the EHA

The key parameters of the EHA are shown in Table 1.

Table 1. The key parameters of the EHA

Symbol	Value	Symbol	Value
c_p	$1674.8\ J/(kg\cdot k)$	ω	$16\ r/s$
ρ	$834.6\ kg/m^3$	p_t	$0.15\ MPa$
α_p	$6\cdot 10^{-4}$	p_p	$21\ MPa$
c_w	$0.828\ J/(kg\cdot k)$	k_{fwp}	$1000\ w/(m^2\cdot k)$
k_{fwa}	$1000\ w/(m^2\cdot k)$	k_{wpa}	$100\ w/(m^2\cdot k)$
k_{waa}	$100\ w/(m^2\cdot k)$	k_{fwc}	$1000\ w/(m^2\cdot k)$
k_{wca}	$100\ w/(m^2\cdot k)$	T_{in}	$20\ c^{\circ}$