Thermal analysis of hydraulic system of landing gear

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Abstract. Landing gear of any aircraft is an important system which aids in takeoff, landing and supports the aircraft on runway. Landing gear system employs a hydraulic actuation system for its operation. Hydraulic system provides pressurized hydraulic fluid for actuation of main and nose landing gear in deployment/retraction mode and brake pressure for braking. Advantage of Hydraulics is small sized actuators due to its high power density, easy control and transmission of power. Hence hydraulics always had been a preferred choice for compact high power systems. During the energy conversion, fluid transmission losses and inherent friction, heat energy is generated in the system which rises the fluid temperature. This heat has to be dissipated by proper means to maintain the system temperature within safe limits. This paper attempts to study the thermal aspects of hydraulic system, heat generation and dissipation to estimate temperature rise profile and steady state temperature.

Keywords: hydraulic actuation system, Landing gear, temperature rise, Lumped heat analysis, steady state temperature

1. Introduction

Retractable landing gear system under study employs Hydraulic actuation system. This system provides pressurized hydraulic fluid for actuation of Main and Nose Landing Gears in retraction and deployment mode. The system also provides hydraulic pressure for brake application. The hydraulic actuation system employs various hydraulic units and components to achieve the desired functionality.

Simulation study of heat generation and transfer in an oil-hydraulic system was performed by Koki Tomioka et al [1], in which they employed bondgraph method. Thermal modeling of electro-hydrostatic actuator was studied by Kai Li et al [2]. YST Raju et al [3] have modeled and simulated the hydraulic actuator of aircraft landing gear. Ray Levek et al [4] have performed the Dynamic analysis of aircraft hydraulic systems. Thermal Calculation analysis and application of the hydraulic system in an aircraft was done by Wang Li et al [5]. Tang Mingyan [6] gave some insight into the aircraft hydraulic system. Heat balance in hydraulic system was described using a system of linear equations in the 727 B hydraulic systems by Ade Abiodun [7]. Aircraft Landing gear...
design was explained in detail in the book Landing gear design by H.G. Conway [8]. The thermal aspects in the planning and designing of modern hydraulic power systems were explained in detail by P.Drexler et al [9].

This paper covers the thermal analysis of hydraulic actuation system to estimate the heat generation and fluid temperature rise during operation of hydraulic system under operation. The hydraulic system is operated during takeoff and landing for retraction and deployment of landing gears. It is also used during brake application during taxi run, rejected take off and during landing. There are a total of 3 actuators and the duty cycle considered here is 30 second continuous operation for retraction and deployment cycle and 60 seconds continuous operation for brake application. The operating pressure is about 160 bar. The paper shall analyze various hydraulic components for heat generation, rejection and fluid temperature rise.

2. Basic Principle:

Hydraulic system utilizes a process of energy conversion and transmission. They have major advantages over other systems of energy conversion in that they achieve a very high energy density. The electrical energy is converted into hydraulic energy by the motor driven pump in a simple manner incurring very few losses.

The process of energy conversion and transmission involves losses in which mechanical and hydraulic energy is converted into heat. The operating temperature is one of the factors governing the efficiency of hydraulic system. If the temperature is too low, the flow resistance is increased and difficulties are experienced with the suction to the pump. If the temperature is too high there are more fluid leaks so losses and wear are greater. The size, nature and duty cycle of the hydraulic installation affects the amount of heat generation and steady state temperature of fluid. In many cases a heat balance evaluation of the hydraulic system provides important insight to the system operation.

3. Heat Gain in Hydraulic system

In hydraulic system, heat is gained from external sources in case of a cold start environment, through various losses and from components.

3.1. Heat gain through heating

In cold start environment, some heating is provided to the fluid to gain some temperature. The heat gain obtained by heating is:

\[
P_w = V_T \cdot c \cdot \rho \cdot \frac{T_1 - T_2}{H}
\]

… (1)

Where

\[ P_w = \text{Heat flow in kW} \]
\[ V_T = \text{Volume of fluid in tank in dm}^3 \]
\[ c = \text{Specific thermal capacity in kJ/kg K} \]
\[ \rho = \text{Density of medium in kg/ m}^3 \]
\[ T_1, T_2 = \text{Temperatures in K} \]
H = heating time in h

Hydraulic oil Properties:
\[
\rho = 890 \text{ kg/m}^3
\]
\[
c = 4.7 \text{ kJ/kg K}
\]

For maintaining a constant temperature in the system which is losing heat due to low ambient temperature

\[
\dot{Q}_w = kA (T1 - T2) \quad \ldots (2)
\]

Where
\[
\dot{Q} = \text{Required Heat gain in kW}
\]
\[
k = \text{Coeff of convection heat transfer in kW/m}^2\text{K}
\]
\[
A = \text{Heat dissipation area in m}^2
\]
\[
T1, T2 = \text{Temperatures of fluid and ambient respectively in K}
\]

a. Heat Gain through Losses

The total power loss of a hydraulic system comprises of a number of separate losses as follows:

\[
P_{loss_{tot}} = P_{l1} + P_{l2} + P_{l3} + P_{l4} \quad \ldots (3)
\]

Where
\[
P_{l1} = \text{Power loss due to efficiencies of components}
\]
\[
P_{l2} = \text{Power loss due to internal leakages}
\]
\[
P_{l3} = \text{Power loss due to throttling}
\]
\[
P_{l4} = \text{Power loss due to flow resistance}
\]

\[
P_{l1} = P_{pump} = \frac{Vp}{600} \left( \frac{1}{\eta} - 1 \right) kW \quad \ldots (4)
\]
\[
V = \text{total volumetric flow in dm}^3/\text{min}
\]
\[
p = \text{Operating pressure in bar}
\]
\[
\eta = \text{Product of all efficiencies.}
\]

\[
P_{l2} = \frac{Vl \Delta p}{600} kW \quad \ldots (5)
\]
\[
V_l = \text{leakage flow or internal leakage in dm}^3/\text{min}
\]
\[
\Delta p = \text{pressure differential in bar}
\]
\[ P_{l3} = \sum \frac{V_t p_t}{600} \text{ kW} \]  
... (7)

\[ V_t = \text{ volumetric flow at throttle in dm}^3/\text{min} \]

\[ p_t = \text{ pressure drop at throttle in bar} \]

\[ P_{l4} = \frac{V \sum \Delta p}{600} \text{ kW} \]  
... (8)

\[ V = \text{ total volumetric flow in dm}^3/\text{min} \]

\[ \sum \Delta p = \text{ total pressure drop in bar (sum of all pressures)} \]

3.2. Heat loss through components

Heat loss happens through the components of hydraulic system, the reservoir, tubes, and heat exchanger at a rate depending on the surface area, wall thickness and fluid velocity.

4. Heat Balance and temperature rise

The temperature of hydraulic fluid depends on the power losses, place of installation and surface area of heat radiating components. And the maximum permitted fluid temperature depends on the type of fluid, system requirements and the operation duty cycle.

Heat gain shall be compared to heat loss, the resultant shall be the heat retained by system over specified period of time. This heat accumulation shall raise the fluid temperature which shall be evaluated.

![Figure 1. Heat balance in Hydraulic system](image)

4.1. Heat Balance Calculation

In heat transfer analysis, assuming Lumped system analysis is a great convenience. But for using it, an appropriate criterion is to be satisfied. The foremost parameter for checking the validity is the Biot number, Bi. Biot number is the ratio of the surface convection to the conduction within the body and the degree of validity of Lumped system analysis is inversely proportional to the value of Bi.

4.1.1. Biot Number.

\[ \text{Biot number, } Bi = \frac{hL}{k} \]  
... (9)

Where \( h \) = heat transfer coefficient in W/m\(^2\)K
\( L_c = \) Characteristic Length

\( K = \) Thermal conductivity in W/mK

Characteristic length, \( L_c = \frac{\text{Volume}}{\text{Area}} \quad \ldots (10) \)

Total volume of the system = \( V_{\text{pump}} + V_{\text{reservoir}} + V_{\text{motor}} + V_{\text{Tubing}} + V_{\text{Actuator}} + V_{\text{Filters}} \)

| Component | Volume (dm\(^3\)) |
|-----------|-------------------|
| Pump      | 0.05              |
| Reservoir | 2.262             |
| Motor     | 0.1               |
| Tubing    | 0.6546            |
| Actuator  | 1.29              |
| Filters   | 0.15              |
| Total     | 4.416             |

Total Area = 1.525 m\(^2\)

Therefore, \( L_c = \frac{(4.4166 \times 10^{-3})}{1.525} \)

\( = 0.00289 \) m

Biot number, \( Bi = \frac{(20 \times 0.00289)}{13000} \)

\( = 4.45 \times 10^{-6} \)

Since, \( Bi << 0.1 \), heat conduction within the body is almost absent and the system is ideal for lumped heat analysis. So Temperature gradient within the system is negligible. Lumped heat analysis will give accurate results.

Heat balance equation,

Heat generated = Energy absorbed + Heat dissipated to surroundings by Convection

4.1.2. Heat Generated.

Heat generation in pump,

\[ P_{\text{pump}} = \frac{V_p}{600} \left( \frac{1}{\eta} - 1 \right) \text{kW} \quad \ldots (11) \]

\[ P_{\text{pump}} = \frac{2 \times 160}{600} \left( \frac{1}{0.89} - 1 \right) = 0.0659 \text{ kW} \]

Heat generated through fluid flow at manifold and filters and tubes

Pressure drop in Manifold block consisting of PRV, NRV and solenoid valves = 2.0 bar

Pressure drop against High Pressure filter = 0.3 bar

Pressure drop against low pressure filter = 1.1 bar

Pressure drop in tube, bends and fittings consolidated ~ 7 bar

Total pressure drop = 2.0 + 0.3 + 1.0 + 7.0 = 10.3 bar

\[ P_{\text{pressure loss}} = \sum \frac{V_p \Delta P}{600} = \frac{2 \times 10.3}{600} = 0.034 \text{ kW} \quad \ldots (12) \]

Heat generated in actuators,
The retraction actuators packing drag pressure contribute to heat generation during movement of piston inside cylinder. Packing drag measured was 3-5 bar. Each actuator takes a flow of approximately 0.65 lpm. 3 actuators are used in system.

Heat loss generated due to packing drag =

\[ P_{\text{actuator}} = \sum \frac{V_{t}P_{t}}{600} = 3 \times \frac{0.65 \times 5}{600} = 0.016 \text{ kW} \]  \[ \text{… (13)} \]

Sum of all the heat generation = 115.92 W

Total Heat generated = 115.92 W (Constant)

Balancing the heat,

\[ Q \, dt = m \cdot c \cdot dT + h \cdot A \cdot (T - T_{\text{amb}}) \, dt \]  \[ \text{… (14)} \]

Substituting,

Heat generated, \( Q = 115.92 \text{ W} \)

Mass, \( m = 2.67 \text{ Kg} \)

Specific heat, \( C = 4700 \text{ J/KgK} \)

Heat Transfer Coefficient, \( h = 30 \text{ W/m}^2\text{K} \)

Total area, \( A = 1.525 \text{ m}^2 \)

\( T_{\text{amb}} = 30 \text{ deg C} \)

We get,

\[ dt = \frac{dT}{1488.92 - 45.75 \, T} \]  \[ \text{…(15)} \]

Integrating from \( t = 0 \) to any time ‘\( t \)’,

\[ t = - \frac{4998.24}{30.5} \left( \ln \left[ 1717.5 - 30.5 \frac{T}{T_{i}} \right] \right) + C \]

\[ t = -163.877 \ln \left[ 1717.5 - 30.5 \left( T - T_{i} \right) \right] + C \]

To find the Constant of Integration \( C \),

At \( t = 0, T = T_{i} \)

\( C = 163.877 \ln \left( 1717.5 \right) \)

\( C = 1220.658 \)

Therefore,
\[ t = -163.877 \ln [ 1717.5 - 30.5 (T - T_i) ] + 1220.658 \]

\[ T - T_i = 32.51 - 0.022 \exp \left( \frac{2003.65 - t}{274.29} \right) \quad \ldots (16) \]

This is the thermal equation defining the temperature rise of the system with respect to ambient temperature. Adding the ambient temperature to the result will give the system temperature at that time. From this equation, the temperature rise of the system with respect to time is determined. Also, the temperature at a given time can also be found. Steady state temperature is the temperature at which the system settles after a certain time. In the thermal profile graph, it is indicated by the point having a slope of zero. The Table 1 displays the system temperature against time.

### Table 2 Theoretical Temperature rise Vs. Time.

| Sl. No | Time(s) | Temperature(°Celsius) |
|-------|---------|-----------------------|
| 1     | 0       | 30.000                |
| 2     | 20      | 32.08601              |
| 3     | 40      | 34.22544              |
| 4     | 60      | 36.21443              |
| 5     | 80      | 38.06355              |
| 6     | 100     | 39.78264              |
| 7     | 150     | 43.56992              |
| 8     | 180     | 45.53219              |
| 9     | 200     | 46.72608              |
| 10    | 250     | 49.3563               |
| 11    | 300     | 51.54823              |
| 12    | 350     | 53.37489              |
| 13    | 400     | 54.89716              |
| 14    | 450     | 56.16576              |
| 15    | 500     | 57.22296              |
| 16    | 600     | 58.8382               |
| 17    | 700     | 59.95997              |
| 18    | 800     | 60.73903              |
| 19    | 900     | 61.28008              |
| 20    | 1000    | 61.65583              |
| 21    | 1100    | 61.91679              |
| 22    | 1200    | 62.09602              |
| 23    | 1300    | 62.22389              |
| 24    | 1400    | 62.3113               |
| 25    | 1500    | 62.372                |
| 26    | 1800    | 62.464                |
5. Experimental evaluation

Hydraulic setup was made in the lab and limited bench testing was carried out with the available resources. The circuit was kept similar to the actual requirement but tube length was restricted due to limited availability of tubes. The hydraulic pump was electric motor driven which takes 24 V DC from a power supply. The system was operated as per its functional requirement and temperature rise of the fluid in reservoir was monitored. The lab setup is shown in figure 1. The testing was carried out at ambient temperature of 30 deg C and system was operated for 30 minutes, the rise in fluid temperature of reservoir was measured. The measured temperature is shown in table 2.

![Figure 2. Lab Testing Setup](image)

| Sl. No | Time (s) | Temperature (° Celsius) |
|-------|----------|------------------------|
| 1     | 0        | 30.3                   |
| 2     | 20       | 35.3                   |
| 3     | 40       | 35.4                   |
| 4     | 60       | 37.2                   |
| 5     | 80       | 36.6                   |
| 6     | 100      | 36.8                   |
| 7     | 140      | 40.5                   |
| 8     | 180      | 40.4                   |
| 9     | 200      | 40.8                   |
| 10    | 250      | 40                     |
| 11    | 300      | 42.6                   |
| 12    | 340      | 42.2                   |
| 13    | 400      | 46.5                   |
| 14    | 480      | 47.9                   |
6. Results and discussion

The theoretical estimation of fluid temperature rise was calculated and experimental measurement of the lab setup was also carried out. A comparative plot of both results is shown in figure 2 below for 30 minutes duration testing.

There is reasonable similarity in temperature rise profile of theoretical estimation with practical measurement, theoretical estimation provided a more conservative results. The difference in steady state temperature is around 10-11 deg C, which can be due to the fact that the exact tube length in actual testing could not be arranged due to limited resources. Although it is assumed that it might not affect the end result due to the fact that additional tube length might have contributed equally in heat addition by internal friction and bending and heat loss by its surface area.

![Figure 3. Thermal Profile of the Hydraulic System](image-url)
7. Conclusion

- The hydraulic system under study was evaluated for various heat parameters and temperature rise was calculated.
- The system achieves a theoretical steady state temperature of approx. 62.51°C after approximately 1 hr of operation.
- The working Duty cycle of system is usually 20 seconds during retraction and deployment cycles and 60 seconds during braking. The temperature rise of the system after half hour experimental operation is within limits (71 deg C).

The thermal system model of the hydraulic system was reasonable and it was able to predict the temperature rise of fluid temperature and steady state operation time duration.

8. References

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