Thermal Modelling of Hydraulic System using an Expert Program

Safaa A. Ghadhban\textsuperscript{1}, Isbeyeh W. Maid\textsuperscript{2} and Intesar k. Atiyah\textsuperscript{3}

\textsuperscript{1}Department of Control & Automation Techniques, Electrical Engineering Technical College, Middle Technical University, Baghdad, Iraq, Email: safaaabid@mtu.edu.iq
\textsuperscript{2}Department of Power Mechanics Techniques, Engineering Technical College-Baghdad Middle Technical University, Baghdad, Iraq, Email: iwm_53@yahoo.com
\textsuperscript{3}Department of Pumps Techniques, Engineering Technical College-AlMusaib University of al Furat al Awsat Technical, Iraq, Email: retaag40@gmail.com

Abstract. The purpose of this work to estimate oil temperature of hydraulic circuit that leads to affect the efficiency of the system. An expert system is built depending on the available knowledge. This model is generated in a computer program named “Thermal Analysis of Hydraulic System (TAHS)”. The program is used to calculate partial power losses at different components of hydraulic system (pump, motor, valves, cylinder, pipe and fittings). The expert system is capable to estimate oil temperature and power loss with different types of (pumps, oils, circuits and actuator dimension). The chosen experimental conditions are oil flow rate, setting pressure, ambient temperature and duty time. The model is validated experimentally and with other works. The results show an acceptable agreement with average deviation about 2.6\% & 6.4\% respectively.

1. Introduction
Hydraulic systems are systems that deals with the generation, transmission, and control of power using pressurized liquids such as oil and water. They are used for activities that required linear and/or rotational motions. A typical hydraulic system consists of a pump, control valves, and hydraulic actuators. The actuator can be either a cylinder or a hydraulic motor. The process of energy conversion and transmission involves losses in which hydraulic and mechanical energy is converted into heat which leads to reduce of oil viscosity which often causes oil leakages and consequently efficiency decreasing\textsuperscript{[1,2]}. One of the factors governing the efficiency of a hydraulic system is the operating temperature, which depends on different issues such as the power losses, pressure limits, the place of installation, the surface area of heat-radiating components (such as tank)\textsuperscript{[3,4]}. There are large numbers of studies about thermal performance of hydraulic systems.

An expert system can be defined as “an intelligent computer program which uses knowledge and inference procedures to solve the problem that is difficult enough to require significant human expertise for its solution” \textsuperscript{[5]}. Increasing the capability of computer systems encourages researchers to develop the processes of design diagnostic, predictive maintenance and management of hydraulic system. Silva \textsuperscript{[6]} designed an expert system that integrates concepts of Design Methodology and Artificial Intelligence in design problem of Hydraulic system. Al-Baldawi and Abtan \textsuperscript{[7]} developed an
expert system prototype (FaulHydra) to assist new engineer in fault diagnosis of hydraulic circuit by providing a gradual analysis of the symptoms of the fault and providing maintenance service or advice. Tomioka et. al.[8] modeled the heat generation mechanism by one-dimensionally using ordinary differential equations and analyzed the heat transfer by three-dimensionally using the partial differential equation of heat conduction. Bahr and John [9] designed a computer program (Hydraulic Components Sizing Calculator) to estimate interactively the proper size of hydraulic components suitable for particular applications. Ghandban [10] developed an expert system prototype (HydroDes) to assist new engineers in designing hydraulic systems by automatically generation a circuit for consideration by the user. V. Tic and D. Lovrec [11] simulated oil flow inside hydraulic tank using CFD. Different hydraulic tank designs were compared with standard one to achieve steady flow through it. Aridhi et. al. [12] presented a pseudo bond graph model of a thermo-hydraulic systems realized through the 20sim software. The simulation shows the temperature difference in the tank according to the cold water mass flow. Kai Li et. al.[13] proposed lumped-parameter thermal-hydraulic models of the hydraulic system in electrohydraulic actuator to perform the thermal analysis. Tarrad et. al. [14] presented study implements the practical updated knowledge of the expertise for both of the hydraulic and thermal fields to improve the performance of hydraulic system. The code is capable to deal with (18) possible connection types of the actuators. Lahari and Reddy [15] attempted to reduce the oil temperature by changing the material and construction of the tank, adding fins over it and improving efficiency of the power unit. The designer procedure of system was modeled using design expert software and error was only 0.01% . Hu Jun-ping and Li Cajun [16] proposed using pseudo-bond graph elements, a method to construct the complete thermal-hydraulic system model based on the heat transfer analysis. Minav et. al. [17], investigated, from thermal viewpoint, direct driven hydraulic system (without control valves). The comparison between the simulation result and the experimental test data validate the modeling developed for the hydraulic system. Chao et. al. [18] analyzed the heating of hydraulic components at constant pressure. The results indicated that the heating value was related with pressure drop and flow. Also, outlet pump pressure was less than safety valve pressure because of pressure loss in pipe of small diameter. Eremin et. al. [19] studied the calculation of the optimal equipment parameters, the lengths and lengths lengths of the pipelines of hydraulic system using mathematical computer model. Badrinarayanan et. al. [20], investigated the hydraulic system of land gear using the thermal system model to predict the temperature rise of oil. Heat generation and dissipation were included in the model to estimate temperature profile.

In this paper, the thermal performance of the hydraulic circuit is modeled using a lumped-parameter. The model was performed based on the analysis of the heat transfer of oil hydraulic flow. This model is employed by an expert program to estimate temperature rise of the system oil. The program called thermal analysis of the hydraulic system (TAHS) which can be verified by comparison program results with experimental ones under same condition. The main purposes of this expert system are calculation detailed power losses of the hydraulic components (pump, valves, actuator, pipe and fitting), thermal estimation of the hydraulic system and calculation heat dissipation from tank and another components. The verified program can be used to analyses the effect of the chosen operating conditions of the hydraulic system.

2. Physical Model

The studied model is a conventional hydraulic system with one or two actuators. Typically, the hydraulic system, of this model, consists of tank, constant displacement pump, relief valve, one or two directional valves and one or two actuators which may be sequent operated by using sequence valve. Pipelines and fittings are included in the model. Figure 1 shows flow chart of hydraulic circuit with two actuators sequent operated.
2.1 Governing Equations of model

The governing equations should be solved after balancing assuming that lumped system analysis is a convenience for the power loss (heat generation) and heat dissipated and energy absorbed equations.

1) Heat Generated (Power Losses)

Any hydraulic system generates internal heat due to pressure losses in hydraulic cylinders, hydraulic motors, connectors, valves and fittings. The total heat produced in any hydraulic system is equal to the total energy losses that occurred in each section or component as shown in the following:

\[ p_{sys} = \sum_{1}^{n} p_{sec} \]  

Where :

\[ p_{sec} = \Delta p_{sec} q_{sec} \]  

The detailed power losses are demonstrated below.

a) Power loss of pump

The pump is accountable for providing hydraulic users with oil that meets the required flow and pressure. The power loss of the pump is due fundamentally to the following aspects due to mechanical friction loss:

Mechanical power loss:  
\[ P1 = P \cdot q_{sec} \cdot \frac{1-\eta_m}{\eta_m} \]  

Volumetric power loss:  
\[ P2 = P \cdot q_{sec} \cdot \frac{1-\eta_v}{\eta_v} \]  

Power loss of pump:  
\[ P_{LP} = P1 + P2 \]
b) Power loss of function valve

The hydraulic system contains many valves of different functions, such as direction valve, throttle, and check valve. There is a certain reduction in pressure between the output and input ports due to the presence of fluid resistance by the valve. Loss of energy per valves is as follow:

\[ P_{L_{\text{val} n}} = \Delta p_n Q_{\text{sec} n} \]  

Total power loss of hydraulic function valve:

\[ P_{L_{\text{val}}} = P_{L_{\text{val} 1}} + P_{L_{\text{val} 2}} + \cdots + P_{L_{\text{val} n}} \]  

Where : \( n = 1,2,3,4,\ldots \) = valve no.

The power loss of safety valve is as follows:

\[ P_{L_{\text{saf}}} = P \ Q_{\text{sys}} \]  

c) Power loss of pipe

Hydraulic oil need to beat the resistance of the pipe, so there is a part of the power losses. The power loss of pipe is:

\[ P_{L_{\text{cond}}} = \Delta P \ Q_{\text{sec}} \]  

d) Power Loss of Hydraulic cylinder

Pressure losses occur in hydraulic cylinders due to flow resistance. The general equation for pressure losses in hydraulic cylinder is:

\[ \Delta P = P_{\text{in}} (1 - \eta_m) \]  

To calculate the power losses that occurred in hydraulic cylinders, equation is:

\[ P_{L_{\text{cyl}}} = \Delta P \ Q_{\text{sys}} \]  

e) Power losses of Hydraulic motor

The power losses occurred in hydraulic motor can be calculated by equation:

\[ P_{L_{\text{mot}}} = \Delta P \ Q_{\text{sec}} \eta_{\text{mo}} \]  

To calculate the power losses which occurred in hydraulic cylinders and motor, equation is:

\[ P_{L_{\text{cyl}}} = P_{L_{\text{cyl}}} + P_{L_{\text{mot}}} \]  

2) Heat dissipated to surroundings by Convection

The equation of heat transfer for convection, the radiation and conduction is ignored for this analysis:

\[ P_{\text{res}} = h \ A_{\text{res}} (T_{\text{oil}} - T_{\text{amb}}) \]  

3) Thermal Analysis for Energy absorbed

The general equation for heat absorbed by the oil of the hydraulic system:

\[ P_{\text{net}} = m_{\text{oil}} C_{\text{oil}} (T_{\text{oil, out}} - T_{\text{oil, in}}) \]  

4) Heat Balancing

In heat transfer analysis, a Lumped of system can be assumed by checking the validity of the Biot number, which is the ratio of the surface convection to the conduction. [21]

\[ \text{Bi} = \frac{h L_c}{K \ V_{\text{volume}}} \]  

\[ L_c = \frac{\text{area}}{\ V_{\text{volume}}} \]  

When the \((\text{Bi} << 0.1)\), the system will become ideal and heat conduction neglected the heat, heat balance equation:

\[ (P_{L_{\text{sys}}}) \ dt = [m_c \ p \ \Delta T + h A (T - T_{\text{amb}})] \ dt \]  

or

\[ \int_0^t (P_{L_{\text{sys}}}) \ dt = \int_0^t [m_c \ p \ \Delta T + h A (T - T_{\text{amb}})] \ dt \]  

Temperature rise of oil can be resulted by integration the previous equation:

\[ T_{\text{oil, } t+1} = T_{\text{oil, } t} + \frac{P_{L_{\text{sys}}}}{h A} \ e^{-\frac{h A \ p \ \Delta T}{c_p} \ t} \]  

Figure 2. Structure of the hydrodynamic part in TAHS.
3. Modeling

Performed Model of the TAHS system is divided into two parts. First is a hydrodynamic - Hydraulic system model which aims to estimate the total power losses of system. Second part is a thermal generic model which aims to estimate temperature profile of the oil. The flow chart of the hydrodynamic and thermal parts is detailed in Figures 2 and 3, respectively.
4. Presentation of TAHS Program

The developed expert program is designed according to available knowledge from domain engineer as an expert and book, papers and catalogs as references. A main part of this knowledge is the governing equations mentioned before. The procedure of program presentation mostly depends on (if-then) rules to choose suitable equations and data from knowledge base. Consequently, the program performs the calculations to present results numerically and/or graphically using user interface. The system (TAHS) consists of four basic parts (power loss, temperature rise, duty cycle, and heat dissipation), as explained in Figure 4.

![Figure 4. The structure of TAHS program](image)

A) Mean Page

The mean page is the interface of the expert system (TAHS) is illustrated, and contain the calculation of power loss, thermal profile, duty cycle, and heat dissipation with international unit system. Specific program limitations flow rate limits (0 – 120 l/min), pressure limits (0 – 170 bar), this page includes entering of specifications such as diameter pipe, cylinder dimensions, hydraulic motor volume and tank volume.

B) Calculations Page

This page contains the specifications required to analysis any hydraulic system. These specifications are pressure, flow rate, oil type, application type, ambient temperature. Pressure and flow rate will be written in the input box for each component. The oil type and application display type bottoms application respectively which can be selected by the user according to the operation of the hydraulic system. The user must complete this page to start performing the required calculations, which are four calculations as shown in Figure 5.

C) Power losses page

The calculation page includes the power loss form and heat dissipation form, the page of power losses shown in Figure 6 Contains the calculations of four parts of the system (TAHS), namely hydraulic pump, actuators, pipe, and valves, as in equation (3).
The four parts includes the following options:

1- Different types and sizes of pumps (gear, vane, and piston pump), and its efficiencies (volumetric and mechanical efficiency), according to equations (3), (5), and (6).

2- Different types of actuators (Hydraulic motor, cylinder), with standard values of bore diameter, rod diameter, and stroke of cylinders and standard values of the volume of hydraulic motor. The calculation is based on equations (10), (11), (12), and (13).

3- Different standard diameters of pipes and fitting which is used to calculate power losses based on equation (9).

4- Different types and sizes of valve (relief, direction, throttling, check, and sequences). The relation contained in this form is based on equation (6), (7), and (8).

D) Thermal Profile page

Thermal Profile of the Hydraulic System is the second page of calculation shown in Figure 7. The user should be insert the required data, which are the total time of system operation, Specific heat capacity of oil, tank size and the operating time of actuators. After the calculation, the diagram of the temperature rise profile appeared.
E) Duty Cycle page

The duty cycle is the third page of calculation. This page contains four types to run the actuator, as a single activity (hydraulic motor or cylinder), or two activity (two cylinders or cylinder and hydraulic motor). The input data of duty cycle are flow rate, diameter, and stroke of cylinder. The stop time of actuators should be input to use in calculations.

F) Heat Dissipation page

Heat dissipation is the fourth page of calculations. The heat dissipation of the tank is calculated depending on the size and surface area of the tank, ambit temperature and temperature of the oil according to equation (14).

5. Experimental Investigation

The proposed models of TAHS are validated by using the experimental tests which performed under different conditions by changing main parameters such as flow rate, pressure, duty time, temperature of hydraulic system, and ambient temperature. Figure 8 shows the experimental setup with the locations of pressure, flow rate, temperature of hydraulic system sensors. The program TAHS is experimentally compared for different tests with a flow rate of (3, 5, 7 l/min) under setting pressure between (20-60 bar) at constant ambient temperature. The duty time of the hydraulic system is 2 sec and operation time 60 min.
6. Validation

The comparison between analytical results and the experimental results showed a good agreement with 2.6%, 5.09%, and 6.6% at flow rate 3, 5, and 7L/min respectively and setting pressure of 60 bar as show in Figures 9, 10, and 11. A close agreement was also observed when comparing the results of present work with other literature survey [20] as show in Figure 12. After validation; the program can be used to study the effects of number of factors acting on thermal performance of hydraulic system.

Figure 9. Comparison between the study experimental and analytical with flow (3l/min) & pressure (60bar) & duty time (2 sec) & ambient temperature (22 °C).

Figure (10): Comparison between the study experimental and analytical with flow (5l/min) & pressure (60bar) & duty time (2 sec) & ambient temperature (22 °C).
7. Conclusion

The conclusions and advantages obtained from the expert program are summarized as:
1. The expert system (TAHS) is capable to handle the thermal performance of the hydraulic circuit.
2. The code has the ability to deal with calculation of power loss for each component of hydraulic system, thermal profile of hydraulic system, duty time and heat dissipation.
3. The expert system (TAHS) is friendly in use to estimate thermal profile of hydraulic circuit to help the designer make suitable decisions.

8. References

[1] Andrew Parr. (1998), "Hydraulic and Pneumatic", Butterworth-Heinemann, Elsevier.
[2] Cundiff, John S. (2001), “Fluid power circuits and controls: fundamentals and Applications”. CRC Press.
[3] Qin Zhang, Carroll E. Goering, (2002), “Fluid Power System”, CRC Press, Boca Raton,
[4] Arthur Akers, (2006), “Hydraulic Power System Analysis”, Taylor & Francis Group, Boca Raton,
[5] Giarratano, J. and Riley, G., (1998), “Expert Systems Principles and Programming”, Third Edition, ISBN: 7-111-10844-2, PWS Publishing Company.
[6] Silva, J. C., (1999), “Concurrent Engineering Perspective of Maintenance Aspects through an Expert System Prototype”, Spring Symposium, American Association for Artificial Intelligence, Stanford University, USA.

[7] Rafa A. Al-Baldawi and Abtan A. M., (2003), “Evaluation of Hydraulic Control Systems by using Expert Systems Technologies”, Master Thesis, Al-Mustansirya University.

[8] K. Tomioka, K. Tanaka, K. Nagayama, K. Tokuda, (2005), "Simulation Model of Heat Generation and Transfer in Oil –Hydraulic System", Proceedings of the 6th IFPS International Symposium on Fluid Power, Tsukuba, P.120-125.

[9] Bahr, M. K. and John, S., (2007), "Software for Fluid Power Technology: Hydraulic Components Sizing Calculator", International Journal of Fluid Power, Vol. 8(3), P.65-67.

[10] Al-Baldawi, R. A. and Ghadhban, S. A., (2008), "Computerized hydraulic Circuit Design by using Expert System Technology", Journal of Engineering and Development, V.12(1), P.44-52.

[11] V. Tic and D. Lovrec, (2012), "Design of Modern Hydraulic Tank using Fluid Flow Simulation", International Journal of Simulation, V.11(2), P.77-88.

[12] Kai Li, Zhong Lv, Kun Lu and Ping Yu, (2014), "Thermal-hydraulic Modeling and Simulation of the Hydraulic System Based on the Electro-Hydrostatic Actuator", Procedia Engineering, Elsevier, V.80, P.272-281.

[13] Emna Aridhi, Mehdi Abbes, and Abdelkader Mami., (2013), “Pseudo bond graph Model of a thermo-hydraulic system”. International Conference on Modeling, Simulation and Applied Optimization, Tunis.

[14] Tarrad, Ali H., Rafea A. Al-Baldawi, and Ahmad A. Al- Issa, (2014)."Implementation of Expert System Modeling to Thermal-Hydraulic Design of Hydraulic Systems.” Proceedings of NAMRI/SME Power, 32038.

[15] M.L.R. Chaitanya Lahari and DR.B. Srinivasa Reddy, (2014), “Enhancement of The Performance of Hydraulic Power Pack by Increasing Heat Dissipation”. International Journal of Computational Engineering Research, V.4 (8), P.13-19.

[16] Hu Jun-ping and Li Ke-jun, (2015), "Thermal-hydraulic modeling and analysis of hydraulic system by pseudo-bond graph", Journal of Central South University, V.22, P. 2578-2585.

[17] Tatiana Minav, Luca Papini, and Matti Pietola, (2016), "A Thermal Analysis of Direct Driven Hydraulics" 10 th International Fluid Power Conference. Dresden, Germany.

[18] Chao Wu, Cong Xu, Xuyao Mao, Bin Li, Junhua Hue, Yiqu Liu, (2017), “Heating Analysis in Constant-Pressure Hydraulic System based on Energy Analysis.” IOP Conference Series: Earth and Environmental Science, V.100(1).

[19] A V Eremin, K V Trubitsyn and VA Kudinov, (2018), "Designing of hydraulic System on Computer Model", IOP Conference Series Earth and Environmental Science, 194.,

[20] S.Badrinarayanan, Kuldeep Singh Bhinder, and V. Ramesh Kumar, (2018), "Thermal Analysis of Hydraulic System of Landing Gear." IOP Conference Series: Materials Science and Engineering.V.402 (1),

[21] Holman, J. P., (1970), “Experimental method for engineers”, McGraw – Hill, Japan, 4th Edition.

Acknowledgments
Authors wishing to acknowledge assistance or encouragement from colleagues, special work by technical staff or financial support from organizations should do so in an unnumbered Acknowledgments section immediately following the last numbered section of the paper.