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ISSN 1812-5638

INFORMATION TECHNOLOGY JOURNAL

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Information Technology Journal 12 (19): 5027-5035, 2013
ISSN 1812-5638 / DOI: 10.3923/itj.2013.5027.5035

Analysis and Simulation Study of Heating Characteristics of the Hydraulic Speeding Soft Brake

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Abstract: Based on elaborating the working principle of the hydraulic speeding soft brake, the study analyzed the heating characteristics of the system in two conditions of non-braking and braking. By using Fluent software, the study simulated temperature fields of key components that electromagnetic directional valve in the non-braking condition and electromagnetic proportional relief valve and oil tank in braking condition. Then, the temperature changes of the internal fluid of valves and oil tank are obtained. The temperature monitoring test system of the hydraulic speeding soft brake is established and the temperature monitoring test is conducted. Also, the temperature changes of the system in two conditions of non-braking and braking are monitored and recorded. Simulation and test results show that the hydraulic loop of non-braking condition of the hydraulic speeding soft brake is approximate zero-damping loop for low heat. Also, they show that the balance oil temperature after thermal energy generated by hydraulic speeding soft brake in braking condition has been cooled through the valve and the cooling tank is far below the normal allowable value (80°C). The valves and oil tank in braking condition have good heat dissipation capability. The research results show that hydraulic speeding soft brake can effectively convert the heat generated by the system and improve the reliability of the system so that it can ensure a reliable braking of the conveyor.

Key words: Hydraulic speeding soft brake, the electromagnetic directional valve, the electromagnetic proportional relief valve, heating characteristics, simulation study

INTRODUCTION

Hydraulic speeding soft brake is a kind of hydraulic brakes with low heat and less wear for downward belt conveyor, which is developed based on the principle of the automatic energy conversion.Due to its characteristics of stable deceleration braking and achieving automatic control easily, hydraulic speeding soft brake is now widely used for the downward belt conveyor. By using hydraulic oil as the working medium, hydraulic speeding soft brake can achieve energy conversion by using hydraulic oil as the working medium, which solves the frictional heating problem that the ordinary hydraulic brake can not solve (Sun and Song, 2008). In the process of working hydraulic speeding soft brake converts potential energy and inertia energy of the conveyor into heat energy that can conduct heat exchange easily and this heat energy can promote oil temperature to rise (Zhang *et al*., 2002). When the system is designed unreasonably, the brake that is in the non-braking condition and braking condition will produce more heat, which will lead to the high temperature of the brake system and the change of structure and properties of hydraulic components (Tian and Song, 1993). In particularly, that will cause the aging deterioration of seals quickly, which can not guarantee the function of breaking system. Seriously, these cases can cause the brake failure of the belt conveyor and may cause the high speed accidents and even casualties (Shen and Wu, 2005).

Based on Fluent software, the study simulated the fields of temperature of internal flow of the key components, electromagnetic directional valve in the non-braking condition and electromagnetic proportional relief valve in braking condition and the oil tank. On the basis of the temperature field simulation, temperature monitoring tests of the hydraulic speeding soft brake has been completed. After the analysis of the simulation and test results, we validate the low heat characteristics of the approximate zero-damping hydraulic circuit in the non-braking condition of the hydraulic speeding soft brake and good heat dissipation characteristics of hydraulic circuit in braking condition of the hydraulic speeding soft brake.

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WORKING PRINCIPLE OF HYDRAULIC SPEEDING SOFT BRAKE

By the principle of energy conversion, the braking system uses brake pump to convert inertia energy and potential energy of downward belt conveyor in braking condition into liquid pressure energy and then converts liquid pressure energy into heat energy which will be dissipated. The entire system has not braking friction pair. So, it will not produce sparks and lead to the failure of brake system and serious security incidents because of the warming of friction pair warming (Ma and Sheng, 2008). The hydraulic principle diagram of the hydraulic speeding soft brake is displayed in Fig. 1.

Non-braking condition: During normal operation of the downward belt conveyor, the hydraulic speeding soft brake is in the unloading condition. The kinetic and potential energy of the work runtime is the power source of transported loose material power. During this stage, the hydraulic speeding soft brake can not have the consumption of this part of the energy and the kinetic and potential energy can not be converted to liquid pressure because of the hydraulic circuit without creating pressure (Li *et al*., 2002). The electromagnetic directional valve (DT1) gets power, which makes oil system be in unloading condition. In the non-braking condition, this oil circuit is approximate zero-damping circuit for low heat. the oil flow direction of hydraulic speeding soft brake is the oil tank →braking variable pump→electromagnetic directional valve (DT1)→oil tank (Zhang, 1995).

Braking condition: When the downward belt conveyor needs to conduct normal stopping brake, emergency brake, or overload over-speed brake, electromagnetic directional valve (DT3) should get power and then make DT1 loses power. The hydraulic circuit needs to build pressure so that redundant inertial energy and potential energy can be converted to liquid pressure and eventually converted into liquid heat. At the same time, PLC controller outputs 4~20 mA current signal (Lu and Hu, 1988). Proportional amplifier controls the electromagnetic proportional relief valve (DT2) and hydraulic system is in braking condition and then DT2 establishes normal braking system pressure. When the braking system pressure is higher than 4 Mpa that is adjustable, brake pump's displacement is converted into a large displacement, at the same time, the braking torque also increases to the needed numerical (Xu, 2005). In addition, PLC controller indirectly detects the actual deceleration by detecting the real-time speed and calculates the required torque of the belt conveyor. Thus

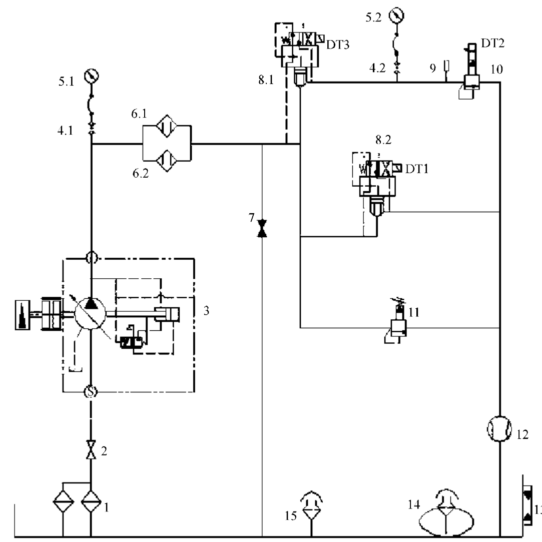

Fig. 1: Hydraulic principle diagram of the hydraulic speeding soft brake, (1) Coarse filter, (2) Ball valves, (3) Brake pump, (4) Measuring pressure joint, (5) Pressure gauge, (6) High-pressure oil filter, (7) Shut-off valve, (8) Electromagnetic directional valve (9) Pressure sensor, (10) Electromagnetic proportional relief valve, (11) Relife valve, (12) Flowmeter, (13) Level liquid thermometer, (14) Air bag, (15) Air filter

the current signal of electromagnetic proportional relief valve can be adjusted, which makes the braking torque generated by the brake pump automatically change with the changes of conveyor belt's loading and then achieve the purpose of constant deceleration (Jiang, 2007).

SYSTEM HEAT CHARACTERISTICS ANALYSIS OF EACH WORKING CONDITION

Hydraulic speeding soft brake generally runs in two conditions (Paramasivam and Arumugam, 2005). One is the normal operation of the belt conveyor, a non-braking condition of the brake system (Li, 2009). The other is the braking condition of brake system when belt conveyor needs stopping brake. The working time of belt conveyor is generally 22 hours a day and the remaining two hours is for maintenance (Li, 2009). In addition to the start-up time and braking time (less than 1 min), most of time belt conveyors is in normal working condition, therefore the brake system is in the non-braking condition for almost 22 h a day. How to make the braking system in the non-braking condition have minimum oil circuit damping and the lowest heat is the key to the design of the system. For braking time that is less than 1 min, hydraulic speeding soft brake should convert all running energy of belt conveyor into heat energy, so the system should have good heat dissipation ability (Lin,1996).

Non-braking condition: According to the working principle of hydraulic speeding soft brake (shown in Fig. 1), we can know that in the non-braking condition DT1 gets power and DT3 loses power, the system is in a state of unloading. The brake variable pump works in small-displacement condition and the displacement is required to maintain the internal normal operation. The research data shows that the damping of a large flow electromagnetic directional valve (DT1) is general for most 0.3Mpa. For example, if the working time of non-braking condition is 22 h, the speed of brake pump n = 1440 rpm, the maximum displacement of the brake pump qmax = 160 mL r^{-1}. By calculation, we can know that the heat generated by the oil return through (DT1) is 18247.5 kJ. So, the final temperature of oil rose is about 25°C. In the non-braking condition, the average time duration of the hydraulic circuit fluid passage to flow in each cycle is about 5s. With each fluid (DT1), the heat which is generated in the oil returns is about 2073.6 naphthalene (2.1 kJ). Namely, when each time system returns oil through the oil (DT1), the temperature rose is about 0.3°C.

According to the above theoretical analysis, choosing electromagnetic directional valve (DT1) for oil returning to oil tank oil makes the oil suffer only a small fluid resistance of 0.3 Mpa and the calculated small temperature rise is of only 0.3°C when oil returning is completed. Also, choosing electromagnetic directional valve (DT1) for oil returning to oil tank makes hydraulic speeding soft brake generate less heat, so this oil circuit is approximate zero-damping circuit for low heat. Electromagnetic directional valve (DT1) is a key component of approximate zero-damping circuit which is specifically designed for reducing heat of hydraulic speeding soft brake in non-braking condition. The structure principle of electromagnetic directional valve (DT1) is displayed in Fig. 2 (Wang, 2004).

Braking condition: When system is in braking condition, the large flow electromagnetic directional valve (DT1) loses power and DT3 gets power, electromagnetic proportional relief valve (DT2) is controlled by the 4-20mA. Based on the principle of constant deceleration, by controlling the size of the valve (DT2) opening, brake system establishes system pressure in order to brake the

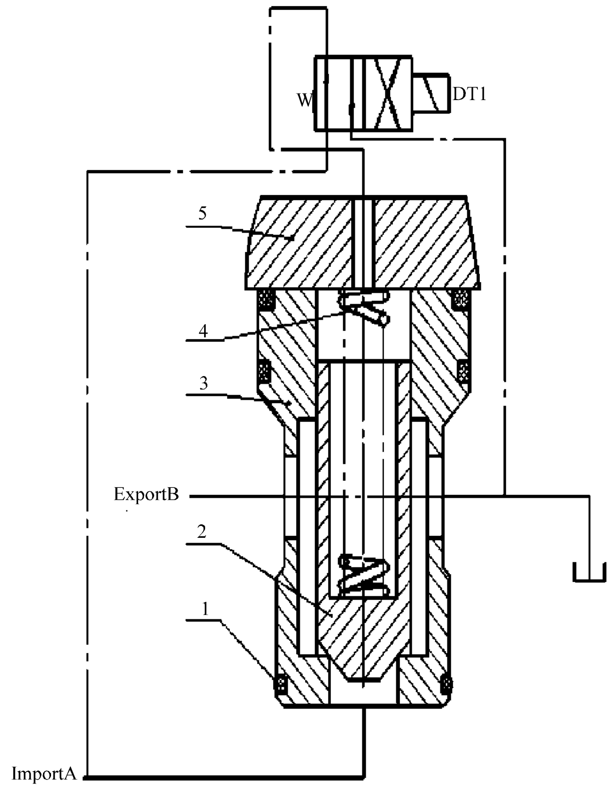

Fig. 2: Structure principle diagram of electromagnetic directional valve, (1) Seal ring, (2) Valve Spool, (3) Valve sleeve, (4) Spring, (5) Cover plate

belt conveyor. At present, the oil flow direction of hydraulic speeding soft brake is the oil tank→braking variable pump→electromagnetic directional valve (DT3)→electromagnetic proportional relief valve (DT2)→oil tank. According to the working principle of hydraulic speeding soft brake, the heat generated in braking condition will be disseminated through the valve (DT2) and the oil tank. The study analyzes the heat dissipation in braking condition taking the key component of the AGMZA-32-type electromagnetic proportional relief valve (shown in Fig. 3) of ZYZ-380 type hydraulic speeding soft brake as an example (Han *et al*., 2010).

In the braking conditions (calculated by 1min), the calculated generated total heat of braking fluid once is about 59, 956.1 kJ, so the oil temperature rose is about 47°C. In the braking condition, the average time duration of the hydraulic circuit fluid passage to flow in each cycle is about 15 sec. With each fluid (DT2), the heat which is generated in the oil returns is about 1175026.9 naphthalene (1175 kJ). Namely, when each time system returns oil through the oil (DT2), the temperature rose is about 10°C.

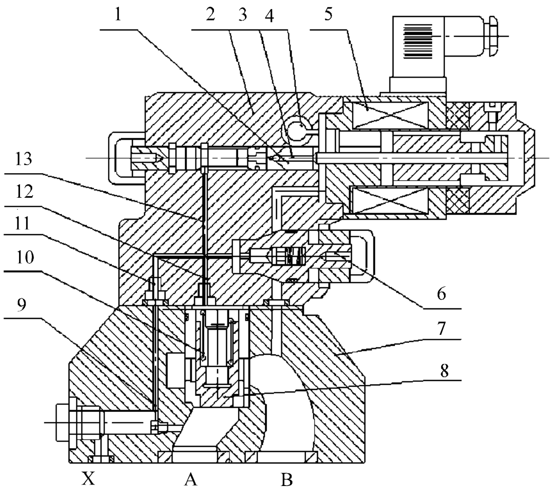

Fig. 3: Structure diagram of the electromagnetic proportional relief valve, (1) Pilot valve spool, (2) Pilot valve body, (5) Proportional solenoid, (6) Pressure limiting valve, (7) Main valve, (8) The main valve spool, (9) Pilot oil flow channel (10) The main valve spring, 3, 11, 12, 13- Orifice, (4) Case drain, (A) The inlet, (B) Overflow outlet, (X) External pilot oil port

SIMULATION STUDY OF HEATING SYSTEMS

The following is the temperature field simulation analysis of the key components of hydraulic speeding soft brake in the non-braking condition and braking condition.

Temperature field simulation of the valve (DT1) based on Fluent: The study takes LDS-25 type high flow electromagnetic directional valve (DT1) as an example and the maximum displacement of the brake pump is 160 mL r^{-1}. According to its actual size and its structure principle (shown in Fig. 2), the calculate model of electromagnetic directional valve (DT1) (shown in Fig. 4) is established by using Gambit which is the preprocessor of Fluent. The computing mesh is shown in Fig. 5. Based on the establishment of appropriate physical and mathematical models, study uses Fluent software to make numerical simulation of three-dimensional flow field of electromagnetic directional valve. The inlet speed of the valve is 1.0 m sec^{-1} and the initial temperature is 291K (18°C). Fluid selects oil, while export and wall boundary conditions select the default value. The model simulation results are shown in Fig. 6, 7, 8.

By the simulation, visualization of internal temperature flow field of electromagnetic directional valve in non-braking condition can be achieved, simulation results can be drawn:

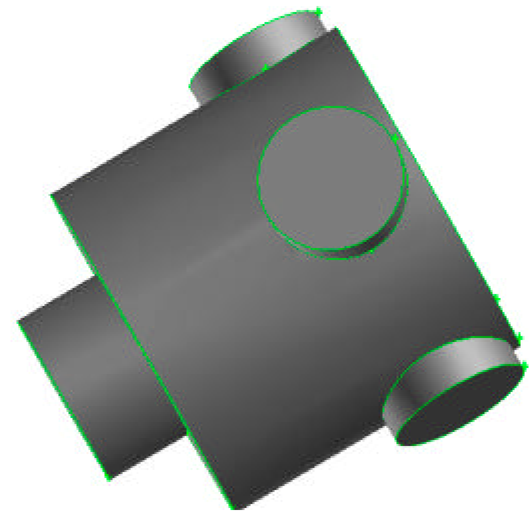

Fig. 4: Calculate model of the solenoid operated directional control logic valve (DT1)

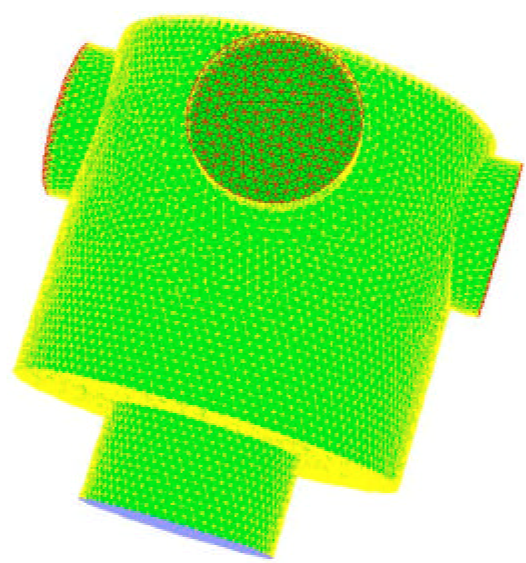

Fig. 5: Computing mesh

- Figure 6, 7, 8 shows that, when the hydraulic oil flows through the electromagnetic directional valve which is fully open mouth in non-braking condition, the temperature rise of oil mainly occurs in the rear of the valve port near the wall of valve body and flow area mutation near the valve outlet. The rising of oil temperature is caused by the slow flow and slow heat dissipation of oil near the body wall and viscous friction. The sudden changes of excessive flow cross-section near valve export leads to the collision-friction among the fluid particles and the collision-friction between the fluid and the wall

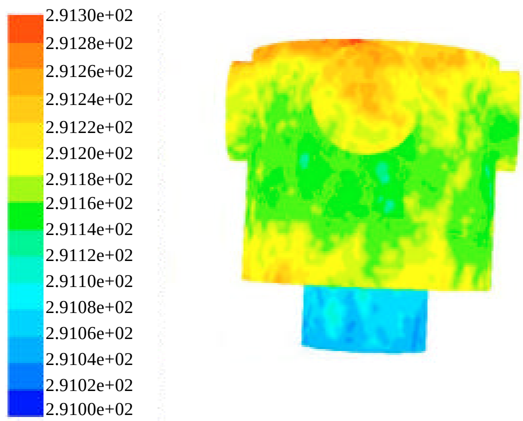

Fig. 6: Computing the temperature nephogram

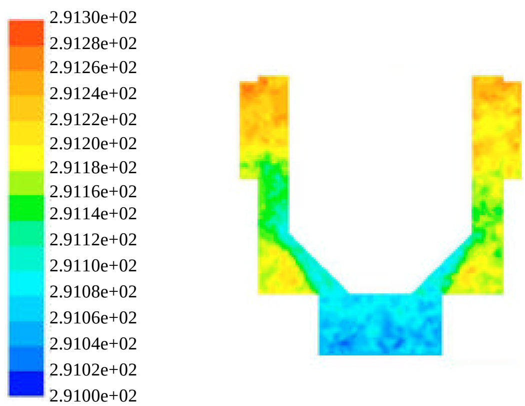

Fig. 7: Symmetry surface the temperature nephogram

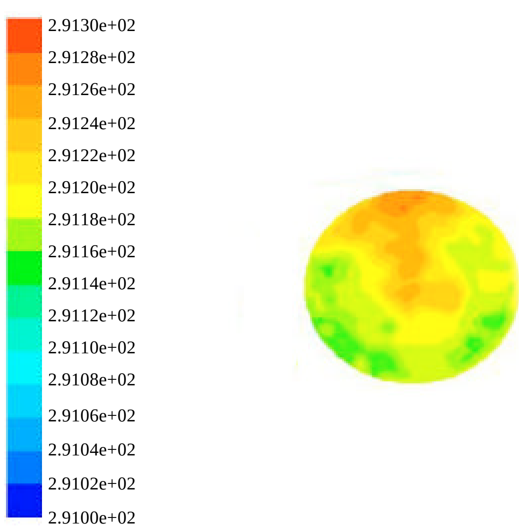

Fig. 8: Export average temperature nephogram

surface and the collision-friction leads to the temperature rise. Because of the viscosity-friction between the oil and the wall surface, the rising of oil temperature of the valve spool and the valve body wall is also relatively high and the temperature of the oil decreases with the increasing of distance between the oil and the wall

- When using Fluent area weighted function to calculate the outlet surface average temperature of the electromagnetic directional valve, the stable convergence temperature is at 291.29 K, namely the temperature rose is 0.29 K (0.29°C). The caused temperature rise is very small and it is close to the theoretical temperature appreciation of 0.3°C. In the long non-braking conditions, it is the key of guaranteed something that the hydraulic speed soft brake system has low heat characteristics. Also, it does not occur that more heat and higher oil temperature will result in damage to the components of the system itself. So, it can ensure the reliability of the hydraulic speeding soft brake

From the above analysis shows that the temperature rise of the electromagnetic directional valve is mainly caused by a sudden change of pressure and speed with the diameter sudden change of the valve internal passages, viscous fluid friction and the friction temperature rise between mutation and the fluid inside. The simulation results show that when the oil flows through the electromagnetic directional valve, the temperature rise is only 0.29°C close to the theoretical temperature 0.3°C. The circuit has good low heat characteristics.

Temperature field simulation of the valve (dt2) based on fluent: The study chooses type of AGMZA-32 electromagnetic proportional relief valve (Fig. 3) to make the flow field simulation. The calculation model and computing mesh of this valve are shown in Fig. 9. For multi-dimensional observation of the flow field and temperature distribution of the oil that flows through the electromagnetic proportional relief valve, two straight lines are located in flow model of the valve and their location is shown in Fig. 9. The first straight line through the orifice is denoted by line 1 and the second straight line through the orifice axis is denoted by line 2. Over the two straight lines, two horizontal planes that section 1 and section 2 are, respectively denoted. The pressure of inlet is 15 Mpa and initial temperature of the oil is 291 K (18°C). The model simulation results are shown in Fig. 10, 11.

By the temperature field simulation, it can be realized the state of the internal temperature field visualization of electromagnetic proportional relief valve. As can be seen from the simulation results:

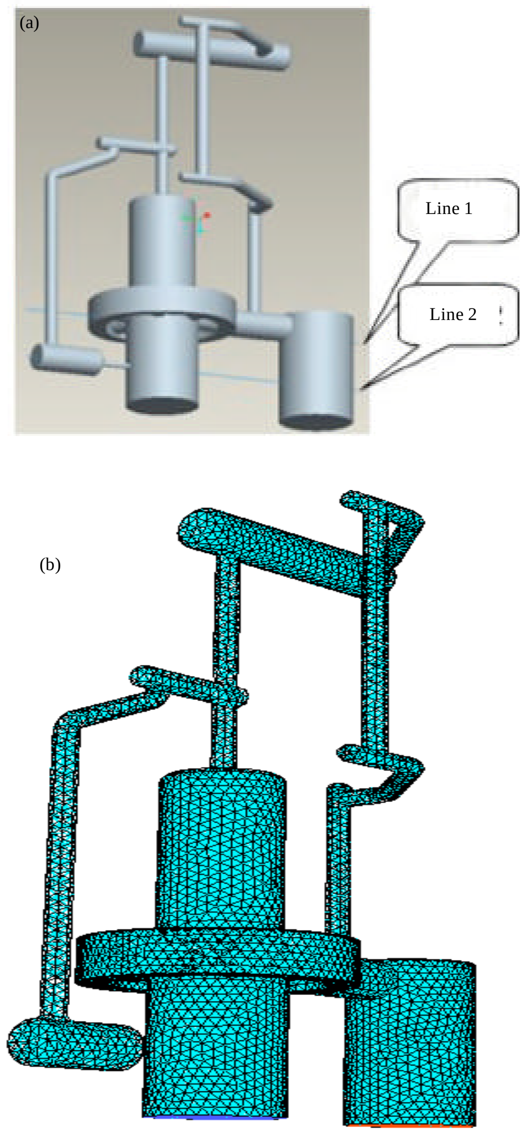

Fig. 9(a-b): Model and mesh, (a) The sketch map of Flow field model, (b) Computing mesh

- As can be seen from the simulation results of Fig. 10, under braking condition, when high pressure oil flows through electromagnetic proportional relief valve (DT2), due to the suddenly changes of the flow section and the clashes between oil and the walls, the oil which passing through the valve clearances between valve sleeve, valve spool and six-flow passage holes onto the valve sleeve has a certain temperature rise. When oil flows through the pilot oil tubing and the orifice, then flows into the pilot valve chamber, oil temperature rise will be higher
- As can be seen from the simulation results of Fig. 11: The oil in the oil export pipelines is composed of hot oil flowing through the orifice and oil flowing through the throttle hole, heat transfer will occur after these two kinds of oil mix up and thermal equilibrium will ultimately be achieved. So the oil temperature in the oil export pipeline is higher than the temperature of oil flowing through the throttle hole and higher than the temperature of oil flowing through pilot oil tubing

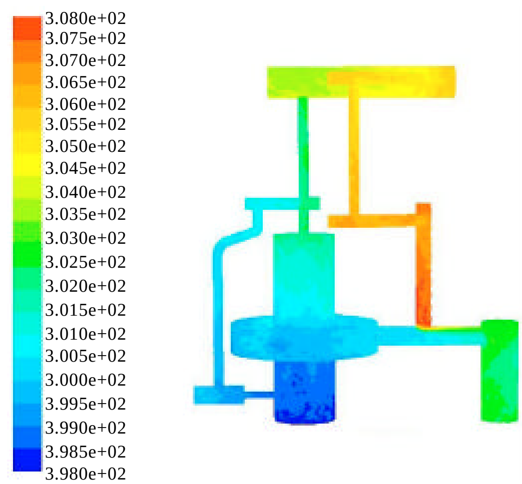

Fig. 10: Computing the temperature nephogram

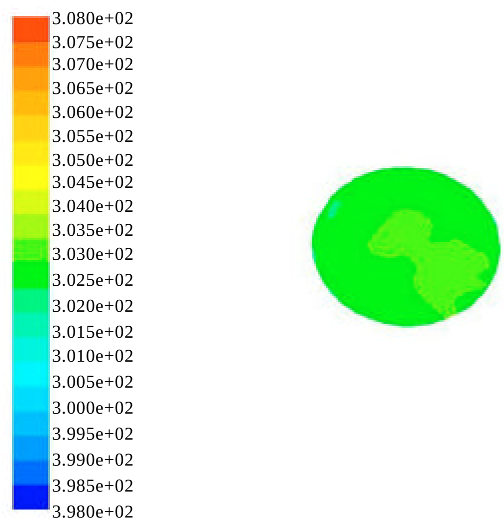

Fig. 11: The export average temperature nephogram

- Using fluent area-weighted function to calculate the average temperature on the export side of electromagnetic proportional relief valve, convergence temperature stabilizes at 306.0012 K in the braking condition. When fluid flows through the electromagnetic proportional relief valve, the temperature rises about 8 K(8°C). The reason why the oil temperature rise is lower than the theoretical calculation by (DT2) temperature of 10°C when the oil returns is that theoretical calculations ignore the good thermal properties of the electromagnetic proportional relief valve. When the oil flowing through the valve, the electromagnetic proportional relief valve will accelerate convective heat transfer with the outside world and constantly emit heat of the oil. So, the oil temperature rise is lower than the theoretical calculation temperature

From the above analysis: The rising of the temperature of electromagnetic proportional relief valve is mainly caused by whirl which is produced from the confluence of valve internal oil, fluid internal viscous friction, friction between the inner wall of oil pipeline and oil etc, which causes These cause the temperature rise of the system. Simulation results indicate that the electromagnetic proportional relief valve has good thermal characteristics so that the oil temperature rise (8°C) is lower than the theoretical calculation temperature(10°C).

Temperature field simulation of oil in the tank: The models of hydraulic oil in the tank are established and meshed by GAMBIT. As shown in the figure, it is the network diagram of calculation model for hydraulic oil in the tank, using tetrahedral mesh to divide the model into 27,837 grid cells, of which there are 5,990 node, as shown in Fig. 12.

Before the simulation by FLUENT, it comes first to determine the boundary conditions of hydraulic oil, namely the convective heat transfer coefficient of each bounding surface and air. Due to the simulation involved into the vertical flat wall, hot side towards the wall and hot face-down wall, it is required to calculate three different heat transfer coefficients. In the case that the brake temperature is 41□ and calculated it by 18□ at the room temperature, by calculation the heat transfer coefficients of vertical surface, the upper surface and the lower surface respectively are 3.87, 4.67 and 1.52 W/(m.K). After the simulation temperature stability, the temperature field distribution is shown in Fig. 13.

The Fig. 13 shows that the temperature on the right side of the diaphragm is generally higher than the one on the other when the hydraulic oil just flows in the tank.And the oil would have a significant reduction after it flows through the diaphragm, convect and exchange heat with the outside world. The highest oil temperature is 41□ and near the fuel tank outlet about 33 □ and the finally balanced temperature is far below the normal allowed value (80 □). By analysis of the temperature field in the tank, the hydraulic speeding soft brake has good cooling

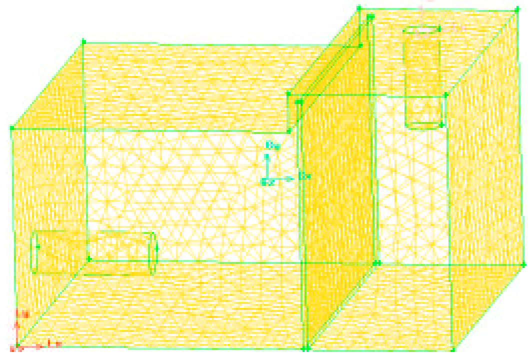

Fig. 12: Meshing of the fluent model in the oil tank

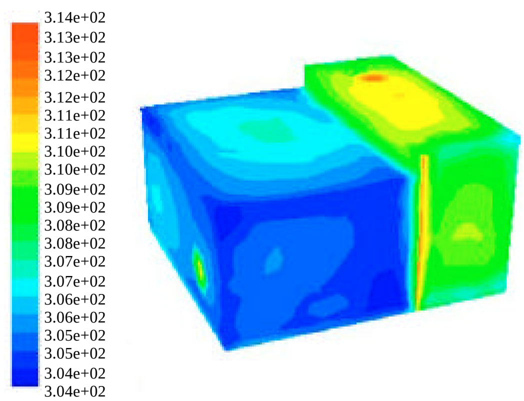

Fig. 13: Temperature field's simulation of the hydraulic oil

characteristics in the braking tank . The tank design does not need additional special conditions and the design based on the normal hydraulic system can meet the requirements of cooling tank.

TEMPERATURE MONITORING TEST

As shown in the Fig. 14, the temperature monitoring test system is established on the base of theoretical calculation for calorific value of hydraulic speeding soft brake working under the conditions of non-braking and braking and the temperature field simulation of key components the oil flows through .The temperature monitoring experiment for the brake is carried out to measure the oil temperature of the system throughout the operating conditions and the results for temperature monitoring parameters is shown in Table 1.

Through analysis of Table 1, the braking variable pump is working at the small displacement and the system is in unloading state during the simulating of non-braking condition, after 22 h the oil temperature near the inlet on the tank's right side rose to 24□ close to the theoretically

Fig. 14: Temperature monitoring test system schematic layout

Table 1: Temperature monitoring experiment result table

Oil temperature neat the inlet/outlet of tank	Simulating of non-braking condition (running 22 h)	Simulating of braking condition (braking for 65 sec)
Theoretical value	25/none	47/none
Measured data	24/21°C	42/32°C

calculated value 25□, when it flows through the diaphragm, convect and exchange heat with the outside world, the oil temperature is reduced to 21□ and only has a temperature liter about 3□ compared to the initial oil temperature 18□, indicating that the calorific value is very small. The measured data during the simulating of non-braking condition reflects that the hydraulic speeding soft brake has the advantage of low fever.

Through analysis of Table 1, the system starts charging and braking which lasts 65 sec when the hydraulic speeding soft brake runs at low liquid resistance for 22 h during the simulating of non-braking condition,the oil temperature just entering the tank is tested for 42□, lowering the theoretically calculated value 47□, due to the fact that theoretical calculation just considers heat produced but ignores the effect of valve and tank for the oil cooling. the oil has a significant reduction after it flows through the diaphragm, convect and exchange heat with the outside world. The oil temperature near the outlet of tank is measured for 32□, the balanced oil temperature is much lower than the normal allowed value (80□). The measured data during the simulating of non-braking condition reflects that the hydraulic speeding soft brake has has a good cooling capacity.

CONCLUSION

According to the above theoretical analysis and simulation study, we can draw the following conclusions:

- For hydraulic speeding soft brake for downward belt conveyor, the circuit which is composed of the electromagnetic directional valve under non-braking is an approximately zero-damping circuit. This circuit greatly reduces the heat of hydraulic speeding soft brake produced on the non-braking state for a long time, which make sure the reliability of systematic working
- According to the temperature field simulation of electromagnetic proportional relief valve and oil tank under non-braking condition, we can know that, electromagnetic proportional relief valve and oil tank under non-braking condition have good thermal properties. After oil flows through the electromagnetic proportional relief valve under braking condition, oil temperature rises to 40°C and the temperature is far below normal temperatures allowed values (80°C). So, the braking system does not require additional specific cooling system. This characteristic avoids the possibility that hydraulic speeding soft brake may trigger a vicious accident due to localized high temperature
- Through flow simulations for two key components on non-braking and braking conditions by Fluent, we can get the flow state of oil in the valve visually. This provides a basis for the analysis on system heating characteristics

ACKNOWLEDGMENTS

The authors would like to thank for the support by National Natural Science Foundation-funded projects under the Grant 51105265 and the support by New Century Excellent Talents Support Program-funded projects under the Grant NCET-12-1038. The authors also thank for the support by Shanxi Natural Science Foundation-funded projects under the Grant 2011021019-1.

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